THE WEAR OF MATERIALS IN HYDRAULIC TRANSPORT PIPELINES

by

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ABSTRACT

The hydraulic transportation of particulate solids through pipelines results in wear of the pipeline walls. The lifetime of the pipeline is determined by this rate of material loss and is therefore critical to the designer. Due to the small amounts of material lost in in-situ tests, requiring in many cases in excess of 1000 hours testing, an accelerated test procedure is necessary.

This work introduces an accelerated method of evaluating materials under simulated pipeline wear conditions. The solids in the slurry and the materials were closely monitored to attain an understanding of their interaction. The wear rate of the materials tested was found to decrease with a decrease in the average particle size and with a rounding of the particles. These changes in particle characteristics occur with time due to comminution within the pump and pipeline. The mechanical properties and wear rates of the materials evaluated were examined to determine whether any relationships existed.

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CHAPTER 1

INTRODUCTION

1.1 HISTORY AND BACKGROUND

There is a large body of literature on the subject of Slurry Transportation and some of the more helpful references are given (8,10,35,42,56,60,61,64,65,71).
The process by which rivers cut into mountain slopes and form river deltas is nature's own slurry transportation system. This process of material removal, transportation and deposition works on the principle that a fast moving turbulent fluid can carry solids in suspension over an indefinite distance. The more turbulent the flow is, the larger the transportable load and the larger the average particle size that the fluid can carry. This is essentially the same principle that governs slurry transportation through pipelines.

Slurry pipeline transportation is the transport of particulate solids in a moving fluid through a pipeline under pressure. The fluid is usually water; however various other fluids with different properties can be used: oil, methanol, etc. A large range of solids can be considered for transportation, for instance: minerals, mineral wastes and agricultural or food products.

The basis for the understanding of slurry transportation are the principles of fluid dynamics and hydrostatics, the study of which goes back as far as Archimedes.

Early examples of slurry transportation were in California during the 1850's where it was used to move gold bearing gravels. The first experimental work on slurry pipelines was carried out by W.C.Andrews of the New York Steam Company. His aim was to transport coal effectively from the mines to his boilers. With this in mind he built a model coal slurry pipeline and received 3 patents for his work in this field.

The year 1914 saw the first industrial slurry pipeline go into operation. It was designed by G.G.Bell and transported 50 tons of coal per hour 600 metres from barges on the Thames river, London, to a nearby power station. In 1951 E.J.Wasp headed the first modern research into slurry pipelines for the Consolidation Coal Company of Ohio, U.S.A.. Closed loop pipelines were constructed to examine the distribution and behaviour of solids carried by a fluid within a pipe and to determine the optimum slurry velocities and the optimum particle size distribution, as well as the rates of corrosion and erosion in the pipeline, brought about by the aqueous environment and the scouring action of the solids fraction of the slurry on the pipe walls. This technology was then used to build the first major slurry pipeline in the U.S.A. - The Eastlake Coal Slurry Pipeline. It transported coal 174 kilometers and operated between the years 1957 to 1963. The pipeline was built in competition to increasing rail costs, but when rail costs fell, it became uneconomical to continue its operation. Since 1957 many slurry pipelines have been built and the literature describes many of them.

Seven basic components of a slurry pipeline system can be identified:

1. the solids to be transported,
2. the pipeline,
3. the hydraulic fluid in which the solids are carried,
4. the pump,
5. the solids preparation plant at the start of the pipeline,
6. the solids separation plant at the end of the pipeline, and
7. the control facility.

The research reported here concerned only the pipeline, in particular the wear of the materials used for constructing slurry pipelines. Many different kinds of materials have been used to manufacture pipelines, and the following are the groups from which the materials are drawn:

Metals
Elastomers (as linings)
Plastics (as linings and piping)
Ceramics (as linings and piping, ie. concrete)
Others, ie. wood staves.

1.2 AIMS AND OBJECTIVES

In the design and construction of a slurry pipeline provision must also be made for the effects of both mechanical and chemical wear and this is the area that this work addresses.

The cause of material failure in pipelines transporting slurries is attributed mainly to abrasion, with corrosion and cavitation as secondary causes. The primary reasons for failure are abusive service conditions and incorrect materials selection. In order to select the correct material for a specific application, it is necessary to evaluate the wear resistance of those materials available, taking into account the specific environment in which they will be used.

A program to evaluate materials for use in slurry transport systems is thus required. This evaluation program must use a test method that simulates the wear conditions that exist within slurry pipelines, ie. abrasive wear, corrosion and cavitation. In general the effect of cavitation in a slurry pipeline is small when compared to abrasion, while the contribution of corrosion to the wear of pipelines is not considered in this study.

The specific aims and objectives of this work were thus:

1. to construct a laboratory test for the accelerated evaluation of materials under slurry abrasion conditions in pipelines, and
2. to evaluate and compare a selection of commercially available pipeline materials.

CHAPTER 2

A REVIEW OF WEAR IN PIPELINES

2.1 MECHANISM OF MATERIAL LOSS

The wear of slurry pipelines is of importance to both the designer and the operator, as it affects the initial cost and the life of the pipeline. The failure of most slurry handling systems is due mainly to abrasion and corrosion, acting individually or together (9).

When transporting solids suspended in liquids, the first consideration is the selection of a velocity which will keep the solids entrained and moving, known as the critical velocity (3). This velocity is dependent on the particle size range, specific gravity, shape and concentration of the solids and the pipe diameter (3,43,50,62). It is also the parameter that determines the rate of material removal. Turbulence which is responsible for particle motion is a product of the slurry velocity. The degree of turbulence is determined by the Reynolds Number (62,68):

$$RE = p.V.D/ u$$

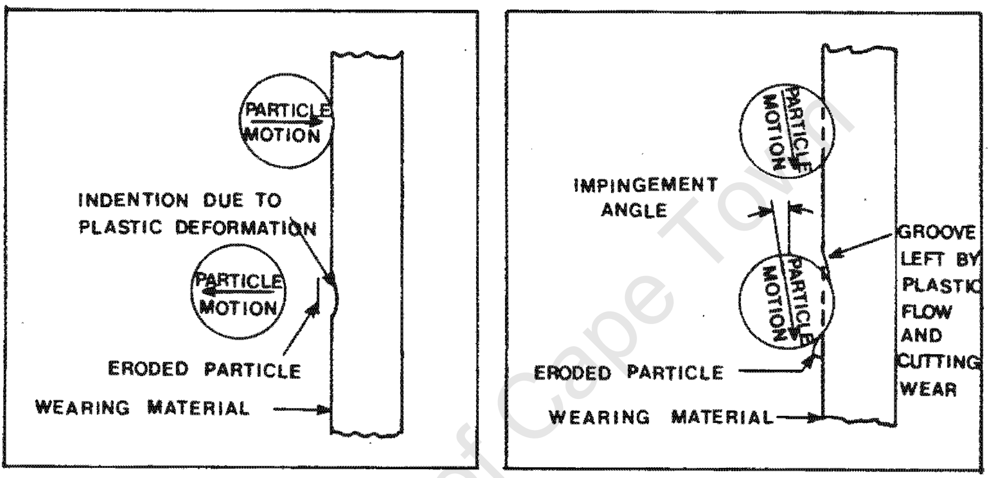
Where

p = the density of the slurry.
V = the velocity of the slurry.
D = the diameter of the pipe.
u = the viscosity of the slurry.

The turbulence is responsible for the formation of eddies. These eddy currents are short lived, but due to their high velocity any particle trapped in them will hit the pipe wall with a far higher than average velocity and thus be capable of transferring more energy to the pipe wall on impact, resulting in greater damage. Particles in the slurry reinforce this eddy current formation (14). As a large particle nears the floor of the pipe, the velocity of the slurry trapped between the particle and the pipe wall will increase rapidly; this increases the velocity of the slurry in this localised eddy. The particles carried by such eddy currents, due to their chaotic motion, impact both the pipe wall and each other as the fluid carries them along. Particle motion is thus determined by eddies, turbulent mixing and collisions. The force of impact and the contact time with the pipe wall are determined by the particle velocity in the slurry and the nature of the particle motion. Particles entrained in eddies can impact the pipe wall at any angle up to 90^0; however for particles in the liquid stream alone, without the effect of eddies, the angle of impact is usually very small.

Essentially two types of mechanical wear are described for pipelines: deformation and cutting wear (50). Deformation wear is the removal of material that occurs when the pipe wall is subjected to repeated particle impacts, resulting eventually in the breaking loose of material from the pipe wall. Cutting wear is the removal of material by a particle moving nearly tangentially along the material surface and is essentially a gouging process. These two types of wear are represented diagrammatically in Figure 1. Cutting and deformation wear are often described as sliding and impact wear respectively by other authors (62).

The actual wear mechanism that predominates is determined by the type of particle motion, which is primarily determined by the slurry velocity (2). It is generally accepted that cutting wear predominates in straight piping; however, wherever an irregularity within the pipeline exists or where there is a bend or component that increases the turbulence within the pipeline, deformation wear predominates.



DEFORMATION WEAR

CUTTING WEAR

FIGURE 1: SCHEMATIC REPRESENTATION OF DEFORMATION AND CUTTING WEAR.
After H.B.Sauermann; HYDROTRANSPORT 8

2.2 FACTORS AFFECTING THE RATE OF MATERIAL LOSS

The wear rate of materials under the action of slurry abrasion is dependent upon many factors (15,36,50):

SLURRY SOLID PHASE PARAMETERS

- particle hardness
- particle size and shape
- particle density
- particle concentration

SLURRY LIQUID PHASE PARAMETERS

- corrosivity
- density and viscosity
- lubricity

MATERIAL PARAMETERS

- composition
- hardness
- elasticity
- orientation
- density or molecular weight
- resilience

FLOW PARAMETERS

- velocity
- flow regime
- pressure

2.2.1 SLURRY SOLID PHASE PARAMETERS

2.2.1.1 HARDNESS

It is generally reported that the harder the solids in the slurry the greater the wear rate of the material used in the pipeline, and that when the hardness of the solids exceeds that of the material, the wear rate will increase rapidly (1,14,15,36,59,51,62). There is, however, very little quantitative information available on the effect of particle hardness on material loss.

The Miller Number is an abrasivity index which attempts to rank solids according to their abrasivity. This test, however, was developed to investigate the wear in reciprocating pumps, and the results from this test are very vague, with large ranges of values for unspecified materials, e.g. mine tailings, with Miller Nos. ranging from 70 to 650 (3,50).

2.2.1.2 SHAPE AND SIZE

The wear rate increases with increasing particle size and this effect is well documented (2,3,15,32,33,36, 39,50,51,62). The effect of shape upon the wear rate is not as well documented and no quantitative information is available; however, it is a well known phenomenon that sharp particles become worn and loose their angularity in slurry transport systems and that the wear rate decreases with this decrease in the particle angularity (1,14,15,18,36,45,50,58, 62).

2.2.1.3 DENSITY

More dense particles are less likely to be entrained in localised high velocity turbulences within the pipeline and are therefore not likely to achieve the higher velocities which would result in high rates of material removal (14,15,36,50, 62). Less dense particles are, however, fully entrained in these turbulences and achieve high velocities resulting in high rates of wear (41,14).

2.2.1.4 CONCENTRATION

Increasing the concentration of solids in the slurry increases the wear rate, due to more particles impacting the pipe walls per unit time (14,15,36,50,62). The rate at which the material loss increases tends to level off after a certain concentration has been reached. This is attributed to the solids impacting with each other due to the decreased mean free path, thus reducing the frequency of effective impacts with the wall (43).

2.2.2 LIQUID PARAMETERS

2.2.2.1 DENSITY AND VISCOSITY

Turcaninov (in 62) states that the relationship between slurry density and wear is parabolic, with wear being proportional to the square of the slurry density. However, he was considering the density of the slurry as that of liquid and solids combined. Considering the liquid phase alone, an increase in the viscosity decreases the rate of wear (36,50). This is probably due to a boundary layer effect, changing the angle of particle impact upon the pipe wall (28).

Material loss is also considered to be proportional to the difference between the solid and liquid densities (50). This parameter determines the settling velocity of the solids and the greater the settling velocity of a particular type of slurry against another type of slurry, the greater will be the wear generated by it.

2.2.2.2 TEMPERATURE

Temperature is important under corrosive conditions. The corrosion rate generally increases with increasing temperature and thus the wear rate is also likely to increase (19,34,50,62). Under certain conditions an increase in the temperature of some materials is associated with a decrease in their mechanical properties (5,16), especially in polymeric materials and this can also result in increased wear rates.

2.2.2.3 CORROSIVITY

Corrosion in pipelines and thus ultimately material loss, is very dependent on the pH of the slurry and on the amount of dissolved oxygen present (34,44,50,54,62). An increase in the pH results in a decrease in the wear rate, similarly an increase in the amount of dissolved oxygen in the slurry results in an increase in the amount of corrosion and thus an increase in the wear rate. These two factors combine to determine the degree of corrosion.

There may be synergism between corrosion and abrasion, which would enhance the rate of wear. Corrosion is not considered in this study as the majority of materials tested are non-corrosive and the period of testing is too short for corrosion to have any effect on the wear rate.

2.2.3 MATERIAL PARAMETERS

2.2.3.1 METALS

It is a well established fact that, as different types of metals of increasing hardness are used, their wear rate decreases (6,12,15,25,36,50,53,62). Yet increasing the hardness of a specific metal by means of work hardening or heat treatment does not necessarily result in a decrease in the wear rate to the same extent that changing the type of metal would. This can be seen from Figure 2. For metals with increasing ductility, it has been found that the wear rate decreases, this has some relationship with the increase in material loss due to work hardening, as work hardening a metal decreases the ductility of that metal (39,32). Increasing the carbon content in both annealed and hardened carbon steels results in a decrease of the wear rate, the opposite appears to be the case when adding Manganese to steel (39,45). When Chromium is added to steel in excess of 13% the wear resistance increases dramatically (39,45).

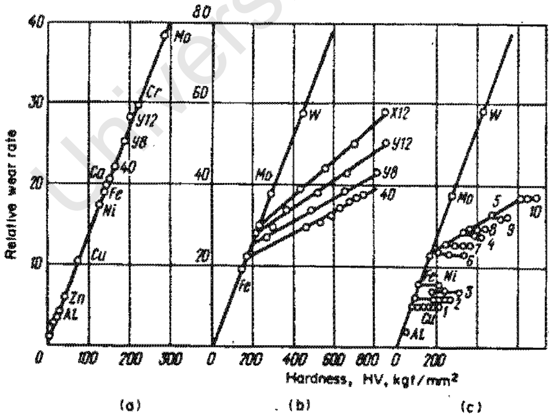


FIGURE 2: THE CORRESPONDENCE BETWEEN RELATIVE WEAR RESISTANCE IN ABRASIVE WEAR AND THE HARDNESS OF A MATERIAL.
a. Technically pure metals and annealed steels,
b. Heat treated steels,
c. Technically pure metals, alloys, and work hardened steels.

2.2.3.2 ELASTOMERS AND PLASTICS

There is a wealth of quantitative data on how long these materials last under specific conditions, but very little information is available as to why they behave that way (4,13,15,17,19,20, 21,34,37,40,41,50,54,58,59,62,69). For elastomers it is considered to be the rebound resilience of the material that determines its wear resistance (14,16,75). The greater the rebound resilience, the faster the material returns to its original shape and the greater the wear resistance. The rebound resilience of elastomers is related to their hardness; for rubbers and polyurethane the relationship is an inverse one (16). The relationships between other mechanical properties and the wear rate have not been established to a satisfactory degree yet, although work has been done in this area (20).

2.2.3.3 CERAMICS

Although much work has been done on materials such as concrete, basalt and various other ceramics (12,15,19,21,24, 34,36,50.52,62,69), it has again been of a qualitative nature and generally standardised to cast iron or mild steel. For advanced ceramics such as sintered alumina or nitride bonded silicon carbide, there does appear to be an inverse correlation between the wear rate and the material hardness (52). Research has also shown fracture toughness and the amount of binder to be important parameters in the wear resistance of these materials (52).

2.2.4 FLOW PARAMETERS

2.2.4.1 FLOW REGIME

The rate of wear is influenced by the characteristics of the flow regime. The flow regime is determined by the slurry velocity, solids concentration, particle size distribution, solids density and pipe diameter. There are 6 distinct flow regimes (15,23,27,43,50,51,62).

1.Homogeneous suspension
All the particles are carried in suspension. The particles are generally smaller than 50μm in diameter.

2.Heterogeneous suspension
Larger particles are present in this slurry than in the homogeneous slurry, with the result that higher velocities are necessary to suspend the load. These large particles tend to move along the lower half of the pipe.

3.Part stationary bed
The heavier material rolls and saltates along the bottom of the pipe with the lighter material in suspension.

4.Moving bed
The heavier material, while still moving, stays in contact with the pipe bottom, while some of the lighter material remains in suspension.

5.Stationary bed 1
The heavy material in contact with the pipe floor does not move, only the surface layers of the solids in the pipeline are transported.

6.Stationary bed 2
There is no movement of the solids in the pipeline at all.

2.2.4.2 SLURRY VELOCITY

Many authors have reported on the effect of velocity on the rate of wear of materials (2,3,15,36,41,43,50,51,62). Essentially they revolve around a relationship with the general form:

$$\mathbf{Wear = k.V^{n}}$$

where

k = a constant.
V = the slurry velocity.
n = velocity exponent.

There is little agreement on what the value of of the exponent n should be, and the reported values range from 0.85 to 6. Marcus (36) quotes a value of n = 2 for ductile materials, and n = 6 for brittle materials.

Pokrovskaya (43) relates the value of the exponent n to the flow regime present in the pipeline and gives the following values and descriptions for n:-

n = 1 : When solid particles move mainly along the bottom of the pipeline.
n = 2 : When a small fraction of the large particles and the finely dispersed material is carried in suspension.
n = 3 : When the slurry tends to homogeneous transportation or when all the solids are suspended in the liquid.

CHAPTER 3

MATERIALS TESTED

The materials chosen for this research were taken from the three main families of materials available: polymers, metals and ceramics.

3.1 METALS

This is a large family of materials of which only two groups were studied, namely medium carbon steels and cast irons. Table 3.1 lists the metals tested, their properties and characteristics. The data is as supplied by the manufacturers. The hardness of the metals is reported as Vickers hardness.

3.2 POLYMERIC MATERIALS

This is a very large and diverse family of materials, which for the sake of this work will be divided into two main groups: thermoplastics, which are materials that are relatively inflexible and can be melted and reshaped indefinitely; and elastomers, which are highly flexible materials and decompose on melting.

3.2.1 THERMOPLASTICS

The materials tested from this family of materials come from the polyolefin group, namely the polyethylenes. These materials, although manufactured via many different routes, are made from the same monomer, ethylene.

Table 3.2 lists the polyethylenes tested, their properties and characteristics. The data is as supplied by the manufacturers. Materials P5 and P6 are High Density Polyethylenes (H.D.P.E.), and materials P1 to P4 are Ultra High Molecular Weight Polyethylenes (U.H.M.W.P.E.). The distinction between these materials is made on their molecular weights.

3.2.2 ELASTOMERS

The elastomers tested came from two groups of elastomeric materials, rubbers and polyurethanes. The rubbers tested included natural rubber and synthetic rubber, polyisoprene, made by polymerising the monomer isoprene.

Polyurethane is formed from a polyurethane prepolymer and a hydrogen bearing curative. The prepolymer is derived from the reaction between a hydrogen donating compound and an excess of diisocyanate. The resultant product is a liquid containing linear urethane linkages. The addition of a hydrogen bearing curative combines with residual NCO groups and the urethane solidifies. Two kinds of diisocyanate are used: Toluene Diisocyanate (T.D.I.) and Diphenylmethane 4.4 Diisocyanate (M.D.I.).
There are three favoured hydrogen donating compounds: polyesters, polyethers and polycapralactones. This results in three further divisions of the two subgroups, thus there are six polyurethane types, of which four were tested in this research. Table 3.3 lists the elastomers tested, their properties and characteristics.The data is as supplied by the manufacturers. Natural rubber is denoted by NR and polyisoprene by IR.

3.3 CERAMICS

The only ceramic tested was Sintered Alumina. The Al_2O_3 content is given as 90% and the density as 3.97g/cm^3. The data is as supplied by the manufacturer.

TABLE 3.1: Metals tested, their properties and characteristics.

METAL	DENSITY	HARDNS	TENSILE STRENGTH	ELONG	COMPOSITION			
					C	Cr	Ni	Mo
	g/cm^3	HV	MPa	%	%			
STEELS								
Bright mild steel	7.83	227	-		.16	-	-	-
Black mild steel	7.83	144	430	21	.2	-	-	-
En24	7.85	302	900	13	.4	1.5	1.5	.25
CAST IRONS								
High chromium white cast iron	7.69	687	-	0	2.6	27	-	-
A.D.I.1	7.2	229	618	4.2	>1.5	-	-	-
A.D.I.2	7.2	525	1318	6.3	>1.5	-	-	-
A.D.I.3	7.2	350	1236	8.0	>1.5	-	-	-

A.D.I. : Austempered Ductile Iron

TABLE 3.2: Plastics tested, their properties and characteristics.

POLYMER	DENSITY	TENSILE STRENGTH	HARDNESS	ELONGATION	MOLECULAR WEIGHT
	g/cm^3	MPa	Shore D	%	(x10^6)
P1	0.935	40	65	>350	4
P2	0.93	40	65	>350	6
P3	0.93	40	65	>350	6
P4	1.14	25	74	>250	6
P5	0.958	35	64	>600	0. 5
P6	0.953	35	64	>600	>0.5

TABLE 3.3: Elastomers tested, their properties and characteristics.

ELASTOMER	DENSITY	TENSILE STRENGTH	HARDNS	ELONG	REBOUND	MODULUS 100%	MODULUS 300%
	g/cm³	MPa	Shore A	%	%	MPa	MPa
RUBBERS							
Linatex(NR)	0.90	17.6	40	484	88.2	-	2.5
IR	0.92	21.9	38	648	89.0	-	0.4
R1(NR)	1.00	15.0	35	800	73.0	-	-
R2	1.00	20.0	45	600	-	-	-
POLYURETHANES							
Vulkollan	1.25	32.5	80	750	52.5	4.7	9.7
Polyester1	1.22	45	80	565	39.5	4.1	8.0
Polyether1	1.05	38	83	565	63.5	6.7	12.0
Polyester2	1.2	46	80	500	40	4.5	9.0
Polyether2	1.1	33	80	470	67	3.5	8.0

NR : Natural rubber

CHAPTER 4

EXPERIMENTAL METHODS

4.1 INTRODUCTION

Many accelerated tests have been documented and many different results have been reported for these accelerated procedures (3,7,62). As methods for ranking materials they are generally adequate. However, even these rankings may vary from researcher to researcher and until some standardisation of the various test methods is achieved, all results must be treated with circumspection. Examples of the more important accelerated procedures used are listed below:-

1. Jet impact tests, where the erodent suspended in air or liquid travelling at relatively high velocity, is blasted onto flat test pieces, with varying angles of impact

2. Specimens in the shape of a pipe are filled with slurry and rotated around either the vertical or horizontal axis.

3. Specimens are rotated through an actual slurry or in a simulated slurry.

4. Specimens are held static while a slurry is made to flow over them.

5. Abrasivity tests where the specimens can be either rotated or reciprocated on the abrasive medium.

The main advantages of these tests is their relatively cheap cost, since the apparatus is generally simple and small, and the methods of measurement straightforward.

Because of the availability of a well established hydraulic transport testing facility at the University of Cape Town, it was possible to develop a method of testing for the evaluation of wear in pipelines that combined both a closed loop rig and a jet nozzle facility. The jet nozzle is attached to the end of the return line of the closed loop rig. The advantage of this method is that the conditions existing in the pipeline and the jet impact test are constant with the exception of the velocity, which is greater in the jet impact test, making it possible to relate the results of the two conditions.

4.2 THE APPARATUS

The test rig consists of seven major components as shown in Figure 3:-

1. slurry reservoir
2. centrifugal slurry pump
3. instrumentation
4. pipeline
5. heat exchange system
6. jet nozzle, bypass system and weigh tank, and
7. specimen holder

4.2.1 SLURRY RESERVOIR

This is a galvanised iron tank with a $1.8m^3$ capacity. The slurry in the tank is kept suspended by two mixer blades that rotate at approximately 30 revolutions per minute for the duration of the test. The entire tank is kept covered by a rubber canopy; this prevents splashing and spray from the mixer blades and the jet impact facility from escaping from the tank.

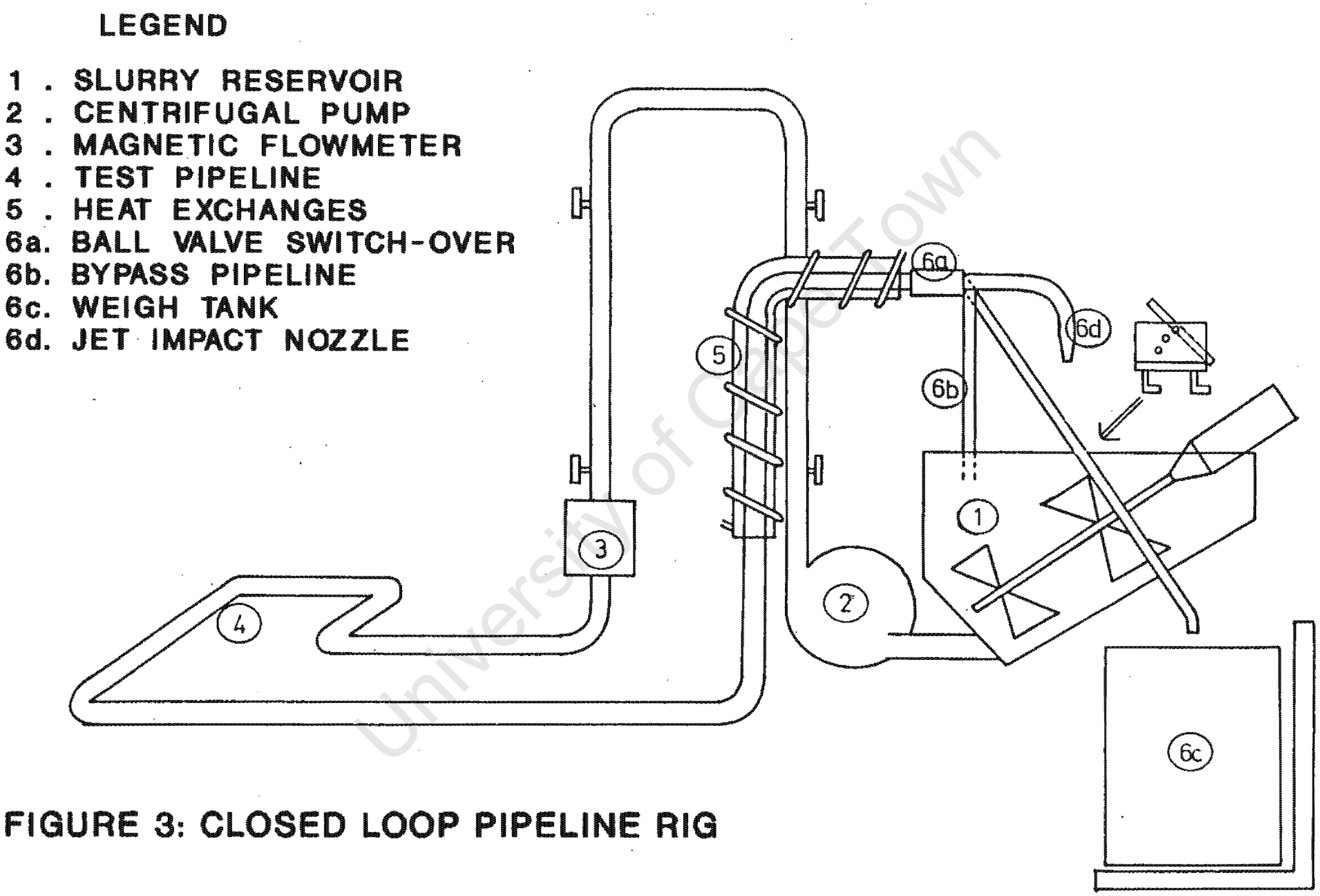


FIGURE 3: CLOSED LOOP PIPELINE RIG

4.2.2 CENTRIFUGAL SLURRY PUMP

The pump is a Warman 4/3D solids handling centrifugal pump, which consists of a rubber lined cast iron casing and a 5-vaned rubber impellor. The pump is driven at a constant speed by a 3 phase 1.7kW induction motor.

4.2.3 INSTRUMENTATION

This section is divided into two parts: solids concentration measurement and slurry velocity measurement. (For a full description of how the concentration and velocity of the slurry is calculated, see Appendix 1.)

Concentration measurement

A counter flow meter is used to measure the delivered volumetric concentration. This is achieved simply by "weighing" the slurry in the up and down pipe sections of the meter by means of pressure tappings. These tappings are two metres apart and each one is connected to a sediment trap, to prevent solids in the pipeline from entering the pressure lines. The pressure difference between the two tappings in either the upwardly flowing slurry pipeline, or the downwardly flowing slurry pipeline, is measured by water manometers. These manometers are attached to the tappings by means of pressure lines that contain water to transfer the pressure pulses. Water for flushing this system is provided by the water mains, and the air necessary in the manometers to attain the differential reading between the two tappings, is supplied by a compressor.

Velocity measurement

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

4.2.4 THE PIPELINE

The pipeline consists of a 57mm inner diameter polyvinyl chloride (P.V.C.) pipeline, with a 900kPa pressure rating. On the return section of pipeline there is a 2 metre section of clear PVC piping, which allows the flow regime present in the pipeline to be observed. The test section of piping consists of bends and straight sections of the materials under test. The bends have a configuration as shown in Figure 4. This configuration prevents premature failure of the bend resulting from the interaction between slurry turbulence due to the bend and that due to a flange directly before or after the curvature of the bend (37). This interaction would result in greater wear in the region directly after the flange. The lead-in and lead-out sections of pipe allow for the normalisation of turbulence due to the bend prior to a flange being reached.

The straight sections of pipe are joined as shown in Figure 5. All three sections are of the same material. This method allows for the central section of pipe to be accurately aligned with the lead-in and lead-out sections of pipe, resulting in a smooth flow of slurry through the central section, which is then used for measuring the wear rate, calculated from the mass loss.

4.2.5 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 by passing it through annular-type mild steel heat exchangers. A 4kW Techniheat refrigeration unit circulates glycol through the heat exchangers, removing the heat generated, and cooling the slurry.

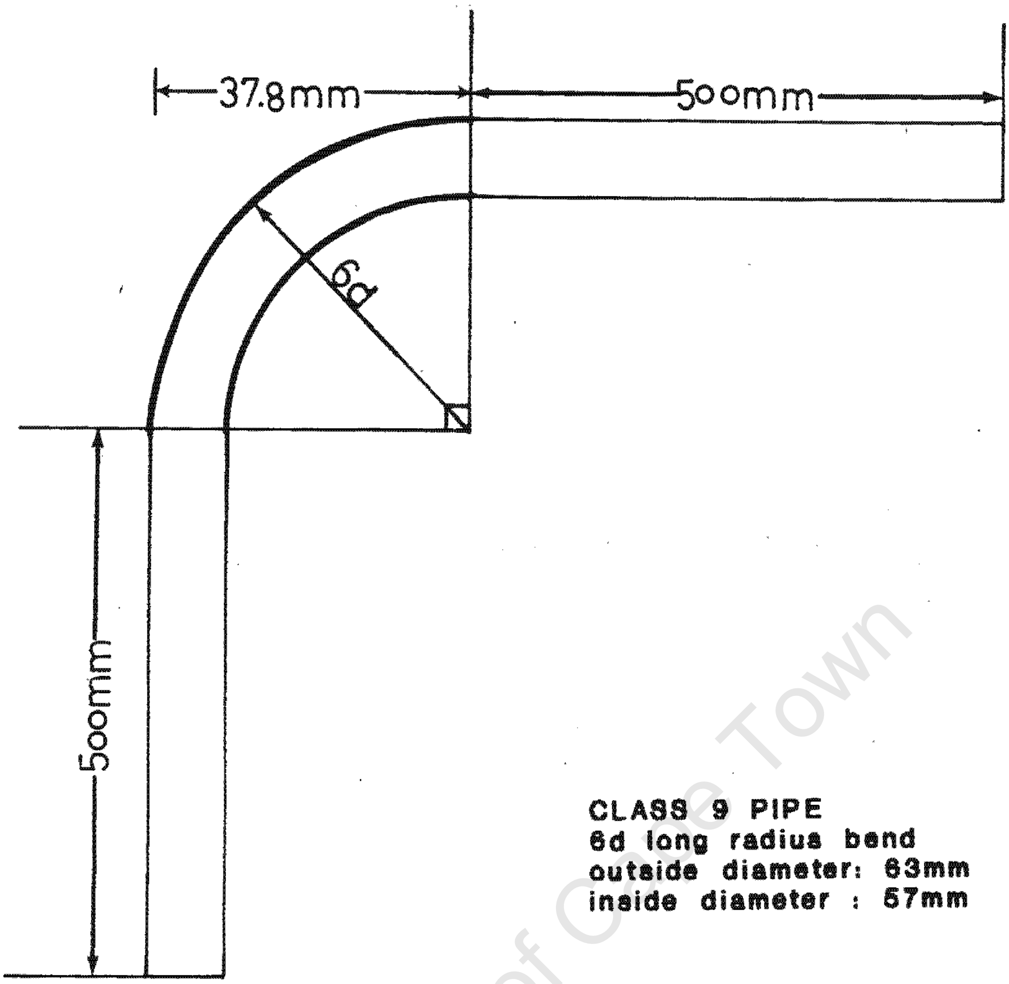


FIGURE 4: TEST BEND CONFIGURATION

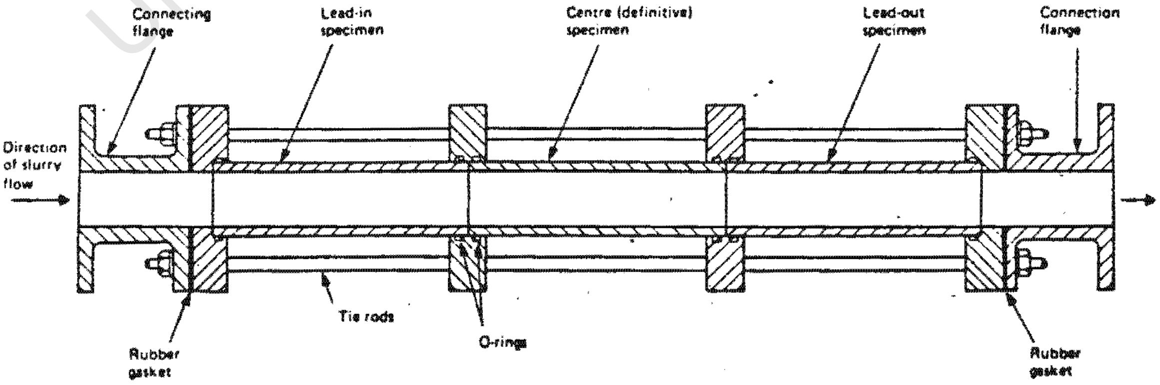


FIGURE 5: TEST PIPE CONFIGURATION
After Baker and Jacobs (4)

4.2.6 JET NOZZLE, BYPASS SYSTEM AND WEIGH TANK

The bypass system consists of two ball valves, both with a 50mm bore. The valves are operated by an air pressure rotary actuator and linked in such a way as to result in the simultaneous opening of one valve and closing of the other. This bypass system (Figure 1:6a) is used to divert the slurry from the jet nozzle (6d) to a bypass line (6b) which returns the slurry to the slurry reservoir, facilitating the change-over of specimens which are situated under the jet nozzle. The nozzle itself is a replacable galvanised iron reducer, reducing the pipeline inner diameter from 57mm to 27mm.

It is also possible for the bypass line to divert the slurry to a weigh tank (6c) through additional gate valves. The use of the weigh tank is described in Appendix 1.

4.2.7 THE SPECIMEN HOLDER

This is a steel plate on which the specimen to be tested is bolted beneath the jet nozzle. The plate can be vertically rotated through 90 degrees, allowing for different angles of impact. The nominal dimensions of the specimens are 150mm x 75mm x 10mm.

4.3 EXPERIMENTAL WORK

Appendix 2 contains a schematic layout of the rig valves and a description of the operation of the rig during a test. The experimental work is subdivided into three sections:

1. Reproducibility of the test proceedure,
2. Jet impact testing, and
3. Pipeline testing.

The conditions of testing are summarized in Table 4.1

TABLE 4.1: EXPERIMENTAL PARAMETERS

Solids size	mm	<6
Solids density	g/cm^3	2.66
Hydraulic fluid		tap water
Volume concentration of solids	%	12
pH of slurry		7
Pipeline velocity of slurry	ms^{-1}	3.6
Temperature of slurry	^{0}C	25 - 32
Pipeline pressure	kPa	250
Head loss	m/m	0.35

4.3.1 REPRODUCIBILITY OF RESULTS

To assess the reproducibility of measuring the wear rate, three test runs with different target materials were carried out. In the first test three specimens of High Density Polyethylene (H.D.P.E.) were exposed sequentially to the jet of slurry for six cycles, with each specimen being impacted for twenty minutes per cycle, ie. a total time of exposure to the jet of 120 minutes each.
Five specimens of bright mild steel were used as the target material in the second test under the same conditions of slurry velocity and concentration as for the H.D.P.E. but using a fresh slurry, ie. a slurry made up with unused solids.

These specimens were also exposed to the jet of slurry for 20 minutes each cycle.

In the third test Ultra High Molecular Weight Polyethylene (U.H.M.W.P.E.) was tested. The conditions were the same as for the previous two tests, also using a fresh slurry, but the five specimens were impacted sequentially for 12 minutes per cycle, thus the total impact time for each specimen was 72 minutes.

The sequential accumulated mass loss (normalised to cm^3 per hour) of these three sets of samples is given in Figure 6 which illustrates:

1. the high degree of reproducibility between individual measurements,
2. that the rate of material loss decreases with slurry lifetime,
3. that a number of specimens could be tested sequentially during the same test run, and
4. that there is apparently no incubation period, with the result that the material loss of each specimen is independant of when in the sequence it was exposed to the jet of slurry.

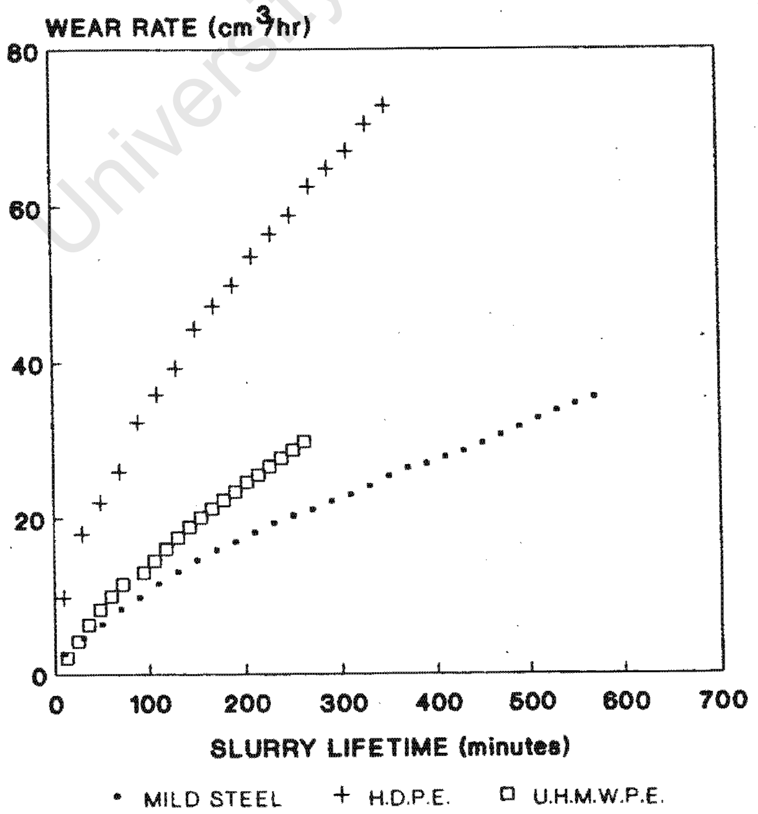


FIGURE 6: CUMULATIVE VOLUME LOSSES FOR ULTRA HIGH MOLECULAR WEIGHT POLYETHYLENE, HIGH DENSITY POLYETHYLENE AND MILD STEEL

The slurry lifetime is defined as the time in minutes that a fresh slurry has been circulating in the system. Figures 7 and 8 are the volume loss graphs for mild steel and U.H.M.W.P.E. respectivly. The graph of mild steel vs slurry lifetime incorporates not only the results from the initial test run but also those results from subsequent tests where mild steel was run as the standard. Again it can be seen that there is a high degree of reproducibility between wear rate measurements at a specific slurry lifetime, even when new specimens are used. The same was found to be true for U.H.M.W.P.E.. The decrease in the wear rate of the test materials with slurry lifetime as shown by Figures 7, and 8, hold true for all the materials tested. This decrease in the wear rate is attributed to the degradation of the slurry over the test period, in particular changes in the particle size distribution and the particle shape of the solids.

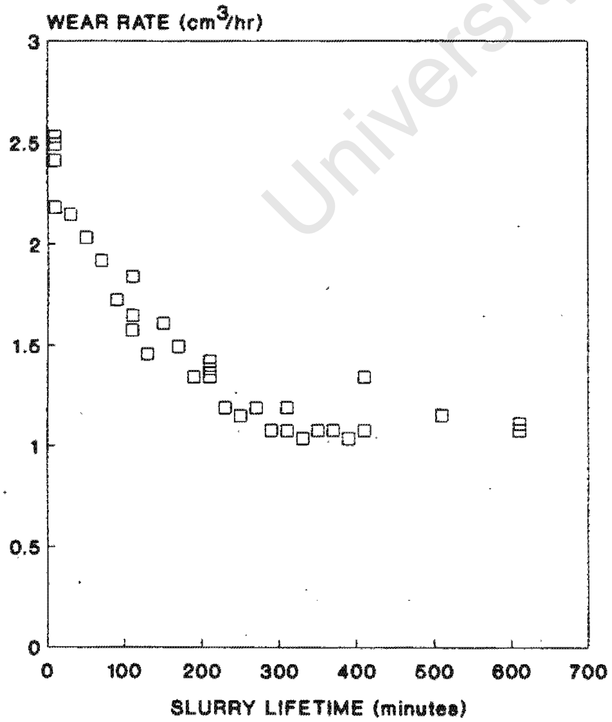


FIGURE 7: INCREMENTAL VOLUME LOSS OF MILD STEEL

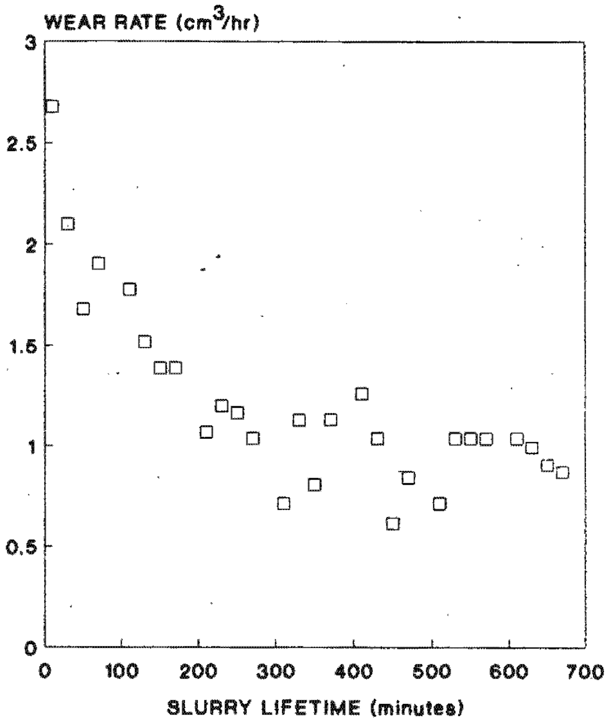


FIGURE 8: INCREMENTAL VOLUME LOSS FOR ULTRA HIGH MOLECULAR WEIGHT POLYETHYLENE

4.3.2 SLURRY SOLID PHASE ANALYSIS

It was found during this work that the solid phase of the slurry undergoes degradation with slurry lifetime. This degradation is defined as the progressive breakdown in particle size and the rounding off of angular particles, caused by the pump and pipeline. Both these changes render the solids less agressive and thus less capable of removing material on impact, both in the pipeline and by the slurry jet. The degradation of the solids was monitored by taking aliquots of the slurry from the return line every hour following the initiation of the test. The sample was allowed to settle and the water decanted off. After drying, it was sieved into the following particle size ranges:-

>5.6mm
4.0 mm - 5.6mm
2.0 mm - 4.0mm
1.0 mm - 2.0mm
0.5 mm - 1.0mm
0.25mm - 0.5mm

The change in shape, not being easily quantifiable, was evaluated optically under a stereo-optical microscope. The solids used in this research were mine tailings. A mineralogical analysis of this material is given in Appendix 3.

4.3.2.1 CHANGE IN PARTICLE SIZE DISTRIBUTION

Figure 9 gives the particle size distribution of the slurry solids for the test run on mild steel; this graph remained the same for all three angles of impact regardless of the type of specimens being tested. This can be better illustrated by figures 10a, 10b and 10c. These are the graphs showing the change in four particle size ranges with slurry lifetime taken from the particle size distribution data for the three angles of impact. To test whether the nozzle or any specimen had an effect on the particle degradation these were removed and a fresh slurry was circulated. Figure 10d is the relevant graph.

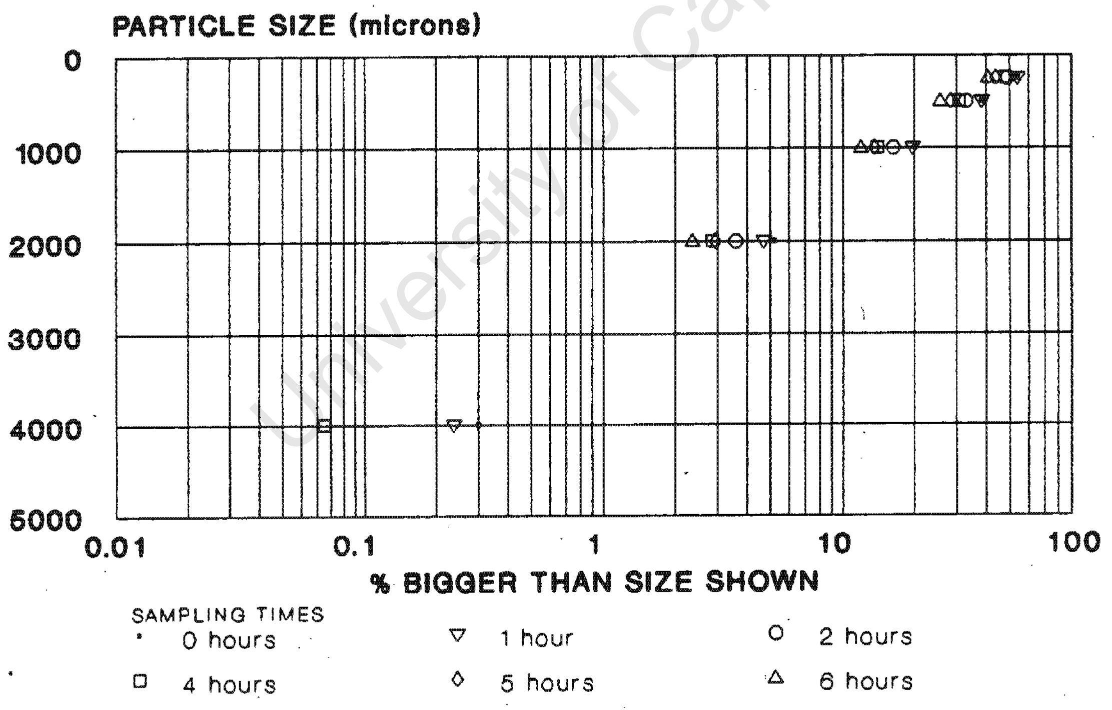


FIGURE 9: PARTICLE SIZE DISTRIBUTIONS DURING SLURRY LIFETIME

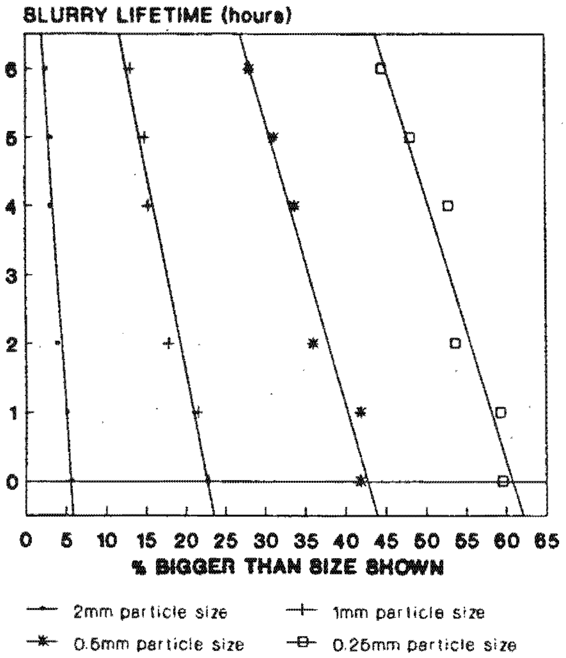


FIGURE 10a: PARTICLE BREAK-DOWN AT AN IMPACT ANGLE OF 20 DEGREES.

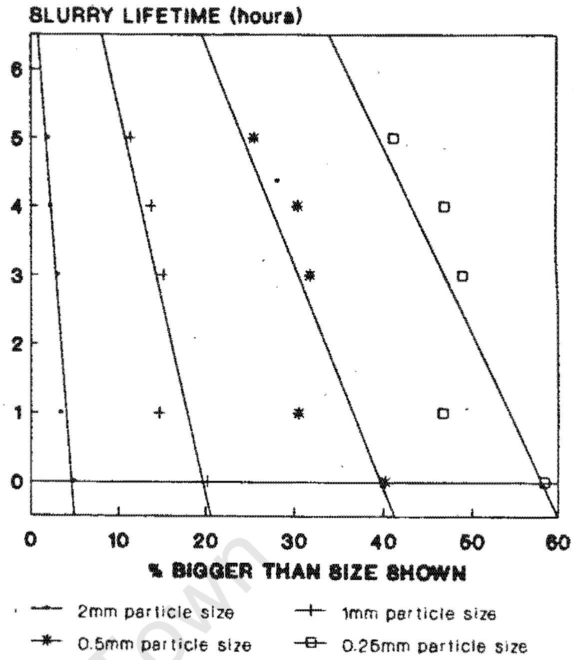


FIGURE 10b: PARTICLE BREAK-DOWN AT AN IMPACT ANGLE OF 30 DEGREES.

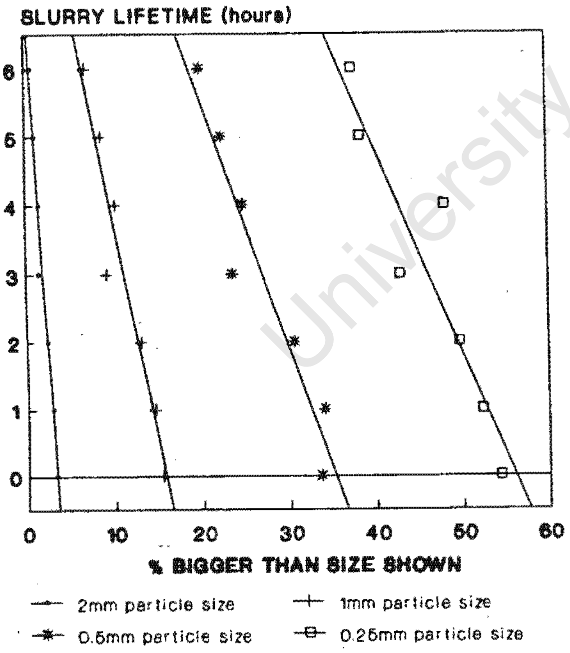


FIGURE 10c: PARTICLE BREAK-DOWN AT IMPACT ANGLE OF 40 DEGREES.

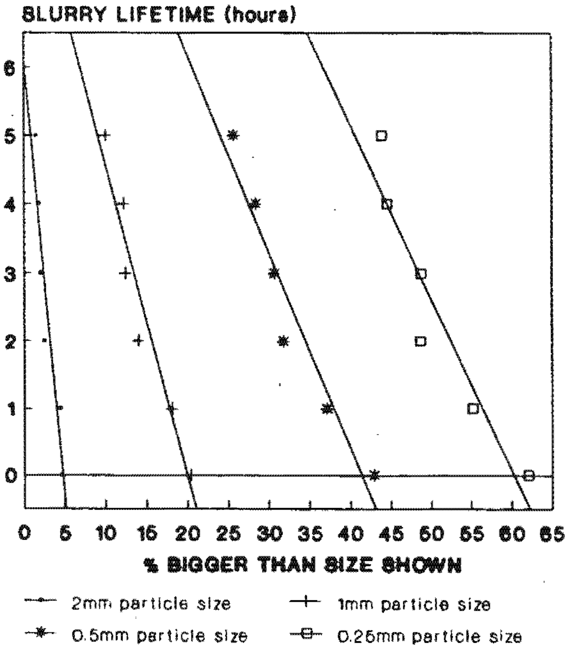


FIGURE 10d: PARTICLE BREAK-DOWN WITH NO NOZZLE OR SPECIMEN PLATE PRESENT.

4.3.2.2 PARTICLE SHAPE

Changes in the particle shape are difficult to quantify, and only a qualitative discussion of this effect is possible at the present. When samples of the particles are viewed under 10X magnification it can be seen that the particles initially have very bright, shiny, sharp, angular shapes. With increasing slurry lifetime the shape changes and tends towards a more rounded shape. Figure 11 is photomicrographs of the particles of the 500 micron size range for samples taken hourly from initiation of the test, for six hours. What can be clearly seen in the first couple of hours is the loss of the sharp sides and the scuffing of the facets with slurry lifetime, resulting in a dulling of the surfaces.

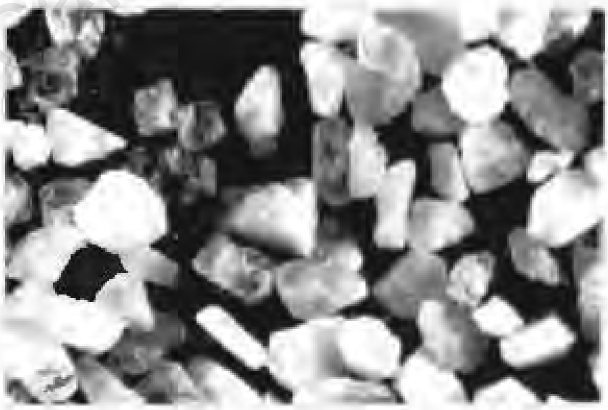
0 hours

1 hour

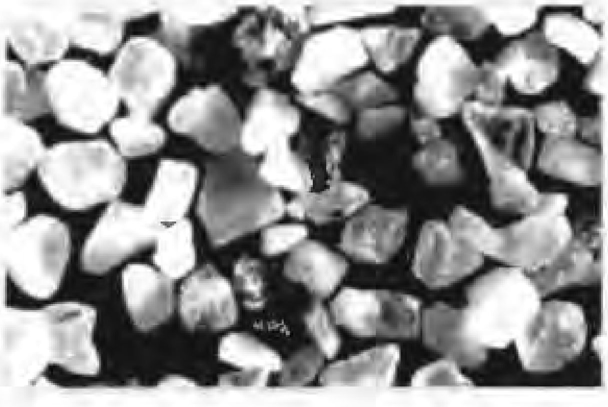
2 hours

3 hours

4 hours



5 hours



6 hours

FIGURE 11: PHOTOMICROGRAPHS OF THE 500μ PARTICLE SIZE DEGRADATION

4.3.3 JET IMPACT TESTING

Based on the experiance gained during the reproducibility study, as described by Steward and Heckroodt (58), the procedure described below was evolved.
Table 4.2 gives the various parameters under which the subsequent evaluations were carried out.

TABLE 4.2: JET IMPACT TEST PARAMETERS

Nozzle velocity of slurry	ms^{-1}	16
Specimen impact angle	°	20/30/40
Specimen exposure duration	min	144
Total test duration	min	720

It was decided to test five specimens sequentially in a single test run due to the long test times required. The initial exposure time to the slurry was 5 minutes per specimen. This resulted in a 20 minute breack while the other 4 specimens were exposed, before the first specimen was exposed to the slurry jet again. After approximatly 3 hours the impact exposures were increased to 20 minutes per specimen until the wear rate levelled off for each of the 5 specimens, when the test is terminated. The total test time was usually between ten to fifteen hours. After each test run was completed, the slurry was disposed of and a new slurry mixed in the slurry reservoir.

The wear rate in grams per hour was calculated by weighing each specimen before the test to an accuracy of 10mg using an electronic balance. After each subsequent exposure to the slurry jet, the specimen was dried and reweighed. Drying involved removing any excess water with a paper towel and then removing the residual dampness with a hair dryer. The specimen was then allowed to stand until it was required for testing, at which stage it was weighed and the mass noted. The resultant mass loss was converted to a volume loss per hour.

At the end of the test run the specimens were studied under a stereo-optical microscope to determine bulk material removal mechanisms and to establish if the different materials have similar wear characteristics.

4.3.4 PIPELINE TESTING

This section of testing, due to the long test periods required, has not produced enough results at this stage to make any comparisons with the accelerated tests. This research is continuing.

CHAPTER 5

RESULTS

5.1 INTRODUCTION

The wear rate, given as volume loss per hour, for the materials were plotted against slurry lifetime. All the graphs are given in Appendix 4. The slurry lifetime is defined as the time in minutes that a fresh slurry has been circulating in the system. Every volume loss value was plotted at the midpoint of the exposure time, ie. the value for the first exposure (total time 5 minutes) was plotted at 2.5 minutes, the second at 7.5 minutes, etc. From these graphs the wear rate at zero time and at 600 minutes for each material and for every condition could be established by interpolation.

5.2 ABRASION RESISTANCE OF MATERIALS

For the first material tested, ultra high molecular weight polyethylene, the displacement of the volume loss vs lifetime curve against that for mild steel was constant throughout the slurry lifetime; however this was not true for other families of materials. It thus became necessary to consider the wear rate of the materials under impact from sharp particles (at slurry lifetime of 0 minutes) and from worn, or blunt particles (at slurry lifetime of 600 minutes). Table 5.1 gives the volume loss results for the materials tested at slurry lifetimes of 0 and 600 minutes, for the three angles of impact.

TABLE 5.1: VOLUME LOSS RESULTS FOR THE MATERIALS TESTED AT THREE ANGLES OF IMPACT.

MATERIAL	VOLUME LOSS(cm^3/hr)					
	0 MINUTES			600 MINUTES		
	20^0	30^0	40^0	20^0	30^0	40^0
STEELS						
Bright mild steel	**2.48**	**3.32**	**2.28**	**1.25**	**1.47**	**1.02**
Black mild steel	2.59	2.80	2.45	1.06	0.92	1.02
En24	1.17	1.60	1.35	0.62	0.75	0.72
CAST IRONS						
High chromium white cast iron	0.20	0.63	0.40	0.09	0.17	0.15
A.D.I.1	-	-	1.9	-	-	0.85
A.D.I.2	1.17	2.40	0.86	0.28	0.30	0.38
A.D.I.3	-	-	1.14	-	-	0.51
RUBBERS						
Linatex	0.35	-	-	0.06	-	-
IR	0.25	-	-	0.04	-	-
R1	0.95	0.60	2.20	0.03	0.07	0.29
R2	2.25	2.50	2.75	0.03	0.16	0.06

TABLE 5.1 CONTINUED..........

MATERIAL	VOLUME LOSS(cm^3/hr)					
	0 MINUTES			600 MINUTES		
	20^0	30^0	40^0	20^0	30^0	40^0
POLYURETHANES						
Vulkollan	0.60	0.75	0.72	0.24	0.14	0.27
Polyester1	0.25	0.62	<0.01	0.25	0.05	<0.01
Polyester2	0.75	2.65	1.55	0.25	-	<0.01
Polyether1	1.44	1.85	1.95	0.26	0.25	<0.01
Polyether2	2.05	2.80	1.47	0.25	0.28	0.25
PLASTICS						
P1	-	-	2.85	-	-	1.27
P2	4.00	4.00	4.45	0.95	1.29	0.95
P3	-	-	3.25	-	-	1.27
P4	3.55	3.55	3.40	1.00	1.26	0.79
P5	-	10.37	-	-	4.74	-
P6	-	9.76	-	-	3.86	-
CERAMIC						
Sintered alumina	1.40	0.70	0.45	0.07	0.11	0.23

The relative abrasion resistance (R.A.R.) for the various materials tested was then calculated for these two slurry lifetimes and given in Table 5.2. In this study the R.A.R. of a test material is defined as the volume of material lost by a standard specimen divided by the volume of material lost from a specimen of the test material under identical conditions. Thus the more wear resistant a material, the greater its R.A.R. value. The standard used in this study was a work hardened mild steel, called Bright Mild Steel.

TABLE 5.2: R.A.R. RESULTS FOR THE MATERIALS TESTED AT THREE ANGLES OF IMPACT.

MATERIAL	R.A.R.sharp			R.A.R.blunt		
	20°	30°	40°	20°	30°	40°
STEELS						
Bright mild steel	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**
Black mild steel	0.9	1.2	0.9	1.2	1.6	1.0
En 24	2.1	2.1	1.7	2.0	2.0	1.4
CAST IRONS						
High chromium white cast iron	12.4	5.3	5.7	13.9	8.6	6.8
A.D.I.1	-	-	1.2	-	-	1.2
A.D.I.2	2.1	1.4	2.6	4.5	4.9	2.7
A.D.I.3	-	-	2.0	-	-	2.0
POLYURETHANES						
Vulkollan	4.1	4.4	3.2	5.2	10.5	3.8
Polyester1	9.9	5.3	large	5.0	29.4	large
Polyester2	3.3	1.2	1.5	5.0	-	large
Polyether1	1.7	1.8	1.2	4.8	5.9	large
Polyether2	1.2	1.2	1.6	5.0	5.2	4.1
RUBBERS						
Linatex	7.1	-	-	20.8	-	-
IR	9.9	-	-	31.3	-	-
R1	2.6	5.5	1.0	41.7	21.0	3.5
R2	1.1	1.3	0.8	41.7	9.2	17.0
POLYETHYLENE						
P1	-	-	0.8	-	-	0.8
P2	0.6	0.8	0.5	1.3	1.1	1.1
P3	-	-	0.7	-	-	0.8
P4	0.7	0.9	0.7	1.2	1.2	1.3
P5	-	0.32	-	-	0.31	-
P6	-	0.34	-	-	0.38	-
CERAMIC						
Sintered alumina	1.8	4.7	5.1	17.8	13.4	4.4

CHAPTER 6

DISCUSSION

6.1 PARTICLE DEGRADATION

From the observations made in section 4.3.2, it can be conluded that:

1. The angle at which the slurry impacts the specimen surface has no effect on the rate of the particle size degradation.
2. The type of specimen surface impacted also has no effect on the rate of the particle size degradation, as many different specimen types were tested and the particle degradation curves remained the same.
3. Neither the actual presence of a specimen in the slurry jet, or the jet nozzle, has any effect upon the rate of the particle size degradation.
4. The size of the particles in the slurry practically decreased linearly in size with slurry lifetime over the period that the slurry was used.

From these observations it can only be concluded that it is the pump and pipeline that are reponsible for the particle degradation. Similar conclusions were arrived at by Baker and Jacobs (4), Truscott (62), and others (2,3,15,50). In Figure 12 the rate at which the size ranges in figures 10 break down is plotted as a function of particle size, and a relationship that is apparently linear is observed. It is thus possible to predict the rate at which other particle sizes break down.

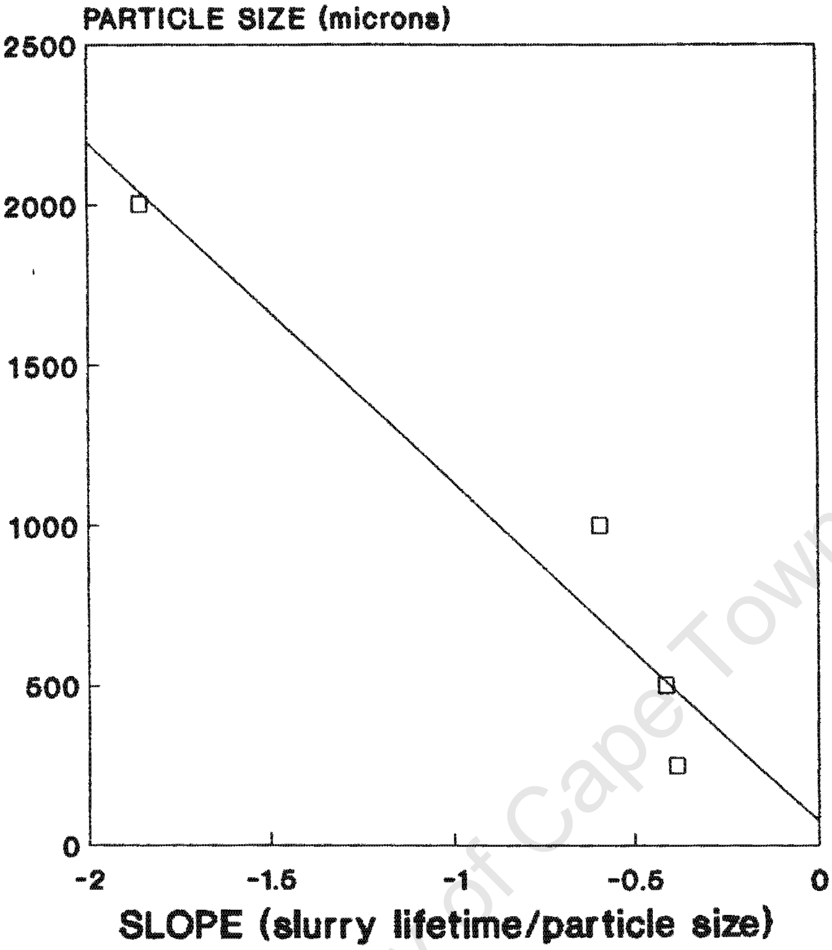


FIGURE 12: THE SLOPES OF THE PARTICLE BREAK-DOWN GRAPHS vs THE RESPECTIVE PARTICLES SIZE.

6.2 MATERIALS

The necessity for two R.A.R. values for the materials tested is due to each family of materials losing material by a different mechanism and at a different rate, under impact from a changing particle size distribution and changing particle shape. This, however, does not mean that the wear mechanism for a specific family of materials changes with slurry lifetime, only that the resistance of the material to the changing particle characteristics changes.

6.2.1 METALS

The mechanism of material removal in all the metals tested was described by A.V.Levy et al (6,22,29,30,31,32), as that of Ductile Platelet Formation. This wear mechanism involves particles impacting the surface of the specimen, producing forged/extruded platelets of metal, that extend over the impacted surface, until a single impact knocks a platelet off. A diagramatic sequence of events leading to material removal by this mechanism is given in Figure 13, while photomicrographic evidence supporting this mechanism is given in Figure 14. A variation to the characteristic "rippled" surfaces of the metals caused by this mechanism was those surfaces of the austempered ductile irons, which had very pitted surfaces due to the preferential loss of their spheroidal carbon content, resulting in small cavities (53). The dutile platelet mechanism of material removal seen on the surface of the steels tested can be considered the same as deformation wear in pipelines described in section 2.1 of Chapter 2 and discussed by Sauerman (50).

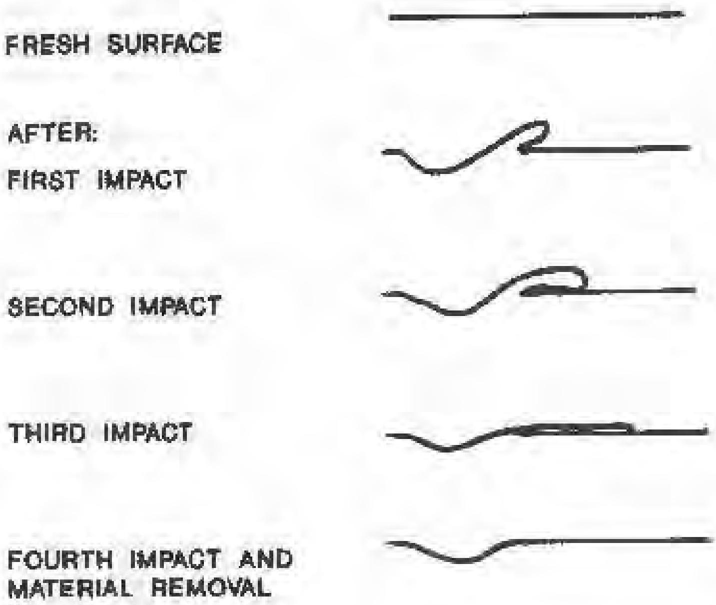
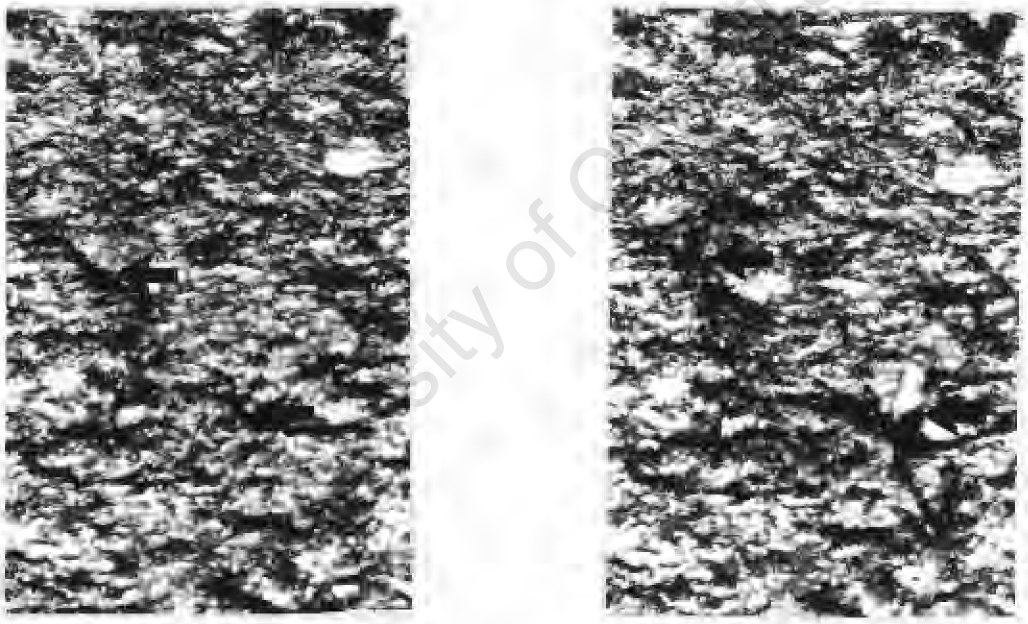


FIGURE 13: SEQUENCE OF EVENTS LEADING TO PLATELET FORMATION IN DUCTILE METALS.



Extruded platelets visible on the metal surface. (indicated with arrows)

Extruded platelet lifted away from the metal surface to facilitate observation and show the method of material removal. (indicated with arrows)

FIGURE 14: PHOTOMICROGRAPHIC EVIDENCE OF PLATELET FORMATION.

From the volume loss results (see Table 5.1), the metals lost maximum material under impact from sharp particles at an impact angle of 30^0, while under impact from blunt particles there is less of a difference in the material lost for the three angles of impact for the individual metals. However, when the R.A.R. values are calculated, the results appear very different. There is little difference between bright mild and black mild steel, while En24 has an R.A.R. value of approximately twice that of mild steel at any of the three angles of impact for both blunt and sharp particles. The cast irons appear to behave differently. High Chromium White Cast Iron has large R.A.R. values for both sharp and blunt particles at an impact angle of 20^0; this is contrary to how other metals wear (39). This brittle behavior is due to the extreme hardness of the metal. In general the cast irons show a large resistance to impact by blunt particles when compared to sharp particle impact. This resistance to blunt particles is due to the high hardness of cast irons.

The observations that can be made about the metals tested are as follows:

1. As the different types of metals were tested it was noted that those with greater hardness had greater wear resistance. This is corroborated by Kruschov (25), Levy and Yau (33) and other researchers. This relationship is shown by Figure 15.

2. Because there is a relationship between hardness and carbon content, increasing the carbon content increases the wear resistance (42). This can be seen in the metals tested here, those with the higher carbon contents have the greater wear resistance.

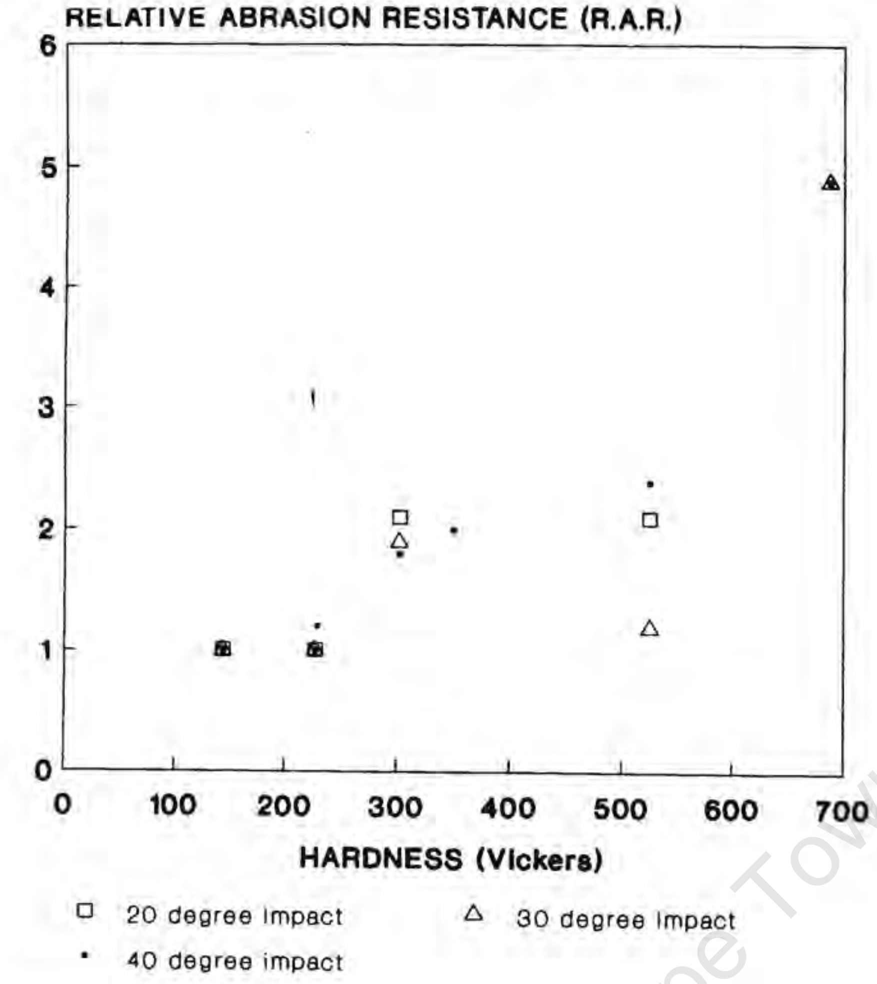


FIGURE 15: HARDNESS OF METALS TESTED vs RELATIVE ABRASION RESISTANCE (R.A.R.).

6.2.2 POLYMERIC MATERIALS

6.2.2.1 RUBBERS

The mechanism of material removal in the case of rubber is mainly by roll formation (14). In this mechanism, graphically explained in Figure 16, an impacting particle comes into contact with the rubber surface, and drags the surface of the elastomer along with it, until the rubber either snaps back or tears, or the particle leaves the surface. A tear begins at the original point of impact, where the rubber surface is experiencing critical elongation, and at right angles to the direction of particle motion. As the rubber surface distorts further, the tear advances, allowing a "roll" or scollop shaped piece of rubber to be removed.

Microscopic investigation of the surface of the rubber specimen at the end of a test revealed that the surface is covered by parallel lines of these rubber "rolls" lying at right angles to the direction of slurry flow. The R.A.R. for impact with blunt particles is greater than that for impact with sharp particles. The sharp particles are able to penetrate the material surface thus removing more material than a rounded particle that can not readily penetrate the material surface. Of interest is the performance of polyisoprene. It has been predicted by the manufacturer to have twice the abrasion resistance of natural rubber, and the results given in Table 5.2 seem to confirm that prediction. From Figure 17 it can be seen that increasing the hardness of the rubber results in a corresponding decrease in the wear resistance of the material.

The hardness of rubbers are determined by the amount of crosslinking of the molecular chains (46,49,74). The greater the amount of crosslinking, the more the movement of the chains over each other are restricted, thus the greater the resistance of the rubber to indentation or the greater the hardness. The resilience of the rubber, on the other hand is a measure of the ability of the rubber to return to its original shape after deformation. With a highly crosslinked rubber this recovery is difficult as the chains entangle making recovery difficult, thus increased crosslinking results in decreased resilience. This inverse relationship existing between hardness and rebound resilience explains why increasing the rebound resilience of a material will increase the R.A.R. of that material.

There is a hierarchy of R.A.R. for these materials that remains unchanged, regardless of the angle of impact or the characteristics of the impacting particles (shape/size) this being (see Table 5.2): (from the most to least wear resistant)

Polyisoprene
Linatex
R1
R2

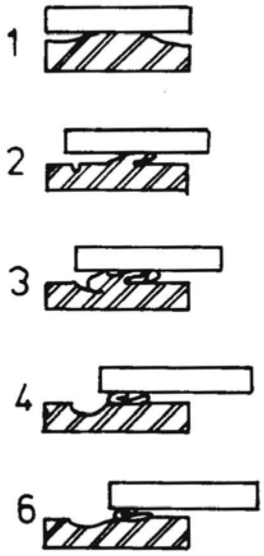


FIGURE 16: SEQUENCE OF EVENTS LEADING TO ROLL FORMATION.

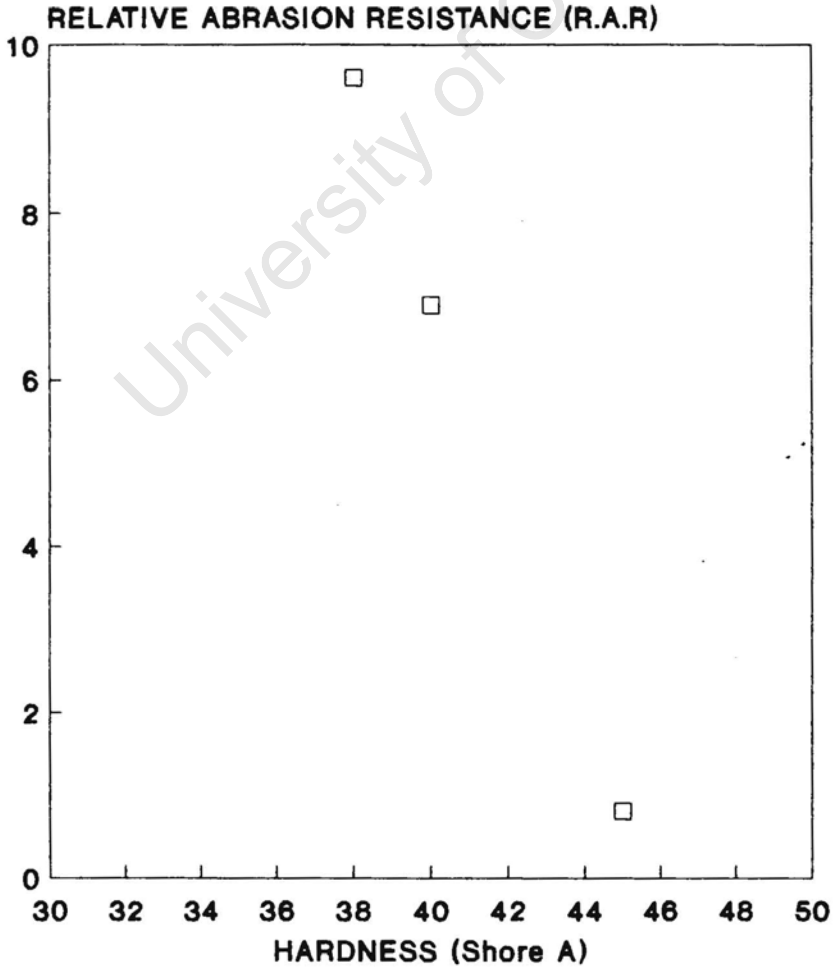


FIGURE 17: HARDNESS OF RUBBER vs RELATIVE ABRASION RESISTANCE AT AN IMPACT ANGLE OF 20 DEGREES

6.2.2.2 POLYURETHANES

Very little is known about the performance of polyurethanes under conditions of wet impact abrasion, and this research did not include enough specimens of this type to determine conclusively any trends, other than that the materials have a higher wear resistance to impact by blunt particles than by sharp particles, as shown in Table 5.2. Microscopic study revealed the mechanism of material removal to be that of cutting and gouging, as can be seen from Figure 18. Roll formation, as seen on the surface of rubber, does not occur in polyurethanes. These materials, however, like rubber, maintain a R.A.R. hierarchy that remains unchanged when the angle of impact is changed, or when the characteristics of the impacting particles change, eg. shape and size, (from most to least wear resistant):

Polyester 1
Vulkollan
Polyester 2
Polyether 1
Polyether 2

The reasons for the high performance of the polyesters could not be investigated due to the small range of materials tested and only general trends could be ascertained. The following table gives the properties associated with the polyester and polyether-types of polyurethanes (5,16).

TABLE 6.1: PROPERTIES ASSOCIATED WITH POLYESTER AND POLYETHER POLYURETHANES

PROPERTY	POLYESTER	POLYETHER
REBOUND RESILIENCE	LOW	HIGH
TEAR RESISTANCE	HIGH	HIGH
HYDROLYSIS	LARGE	SMALL
MECHANICAL PROPERTIES	HIGH	LOW

The mechanical properties include: elongation, tensile strength, hardness and modulus. It can be concluded from this table that the performance of a polyurethane is based on its tear resistance and other mechanical properties. This would, however, need further testing, using polyurethanes with properties extending over a wider range of values.

FIGURE 18: MECHANISM OF MATERIAL REMOVAL IN POLYURETHANES. Examples of cutting and gouging.

6.2.2.3 POLYETHYLENES

Due to the poor performance of the Ultra High Molecular Weight Polyethylenes as regards their resistance to material loss, only two materials, P2 and P4, were tested at the three angles of impact. These two materials display a similar difference between the R.A.R. results for impact with blunt and sharp particles. The same is true of the High Density Polyethylenes, P5 and P6. However the U.H.M.W.P.E. materials (P1-P4) loose approximately four times the volume of material under impact from sharp particles than under impact from blunt particles, whereas the H.D.P.E. materials (P5 and P6) loose approximately twice the volume of material to sharp particles than to blunt particles.

Material removal is initiated by an incoming particle that damages the surface, but does not remove any material. The material is lifted away from the impact area but remains attatched to the surface by thin tendrils of the plastic, until a single particle impact destoys these "tendrils" of plastic and removes the entire deformed piece of material. Thus material loss is dependent on the number of particle impacts, in respect of the number of impacts necessary to create a situation where only one particle is required to remove the deformed material. The polyethylenes tested all had very similar properties of hardness, tensile strength, elongation and resilience. The only property that changed over a wide enough range to study was the molecular weight. Figure 19 shows that a linear relationship exists between the R.A.R. and the molecular weight of polyethylenes. The molecular weight is determined by the length of the molecular chain and it can be concluded that the longer the molecular chain the greater will be the wear resistance of that material.

The nature of this test, however, was far too aggressive for these materials in terms of the large size of the impacting particles. According to local industrial users, H.D.P.E. piping has proved very successful (37,59) in transporting very fine slurries such as gold tailings. However, under conditions of impact, such as bends and at junctions, failures occur frequently.

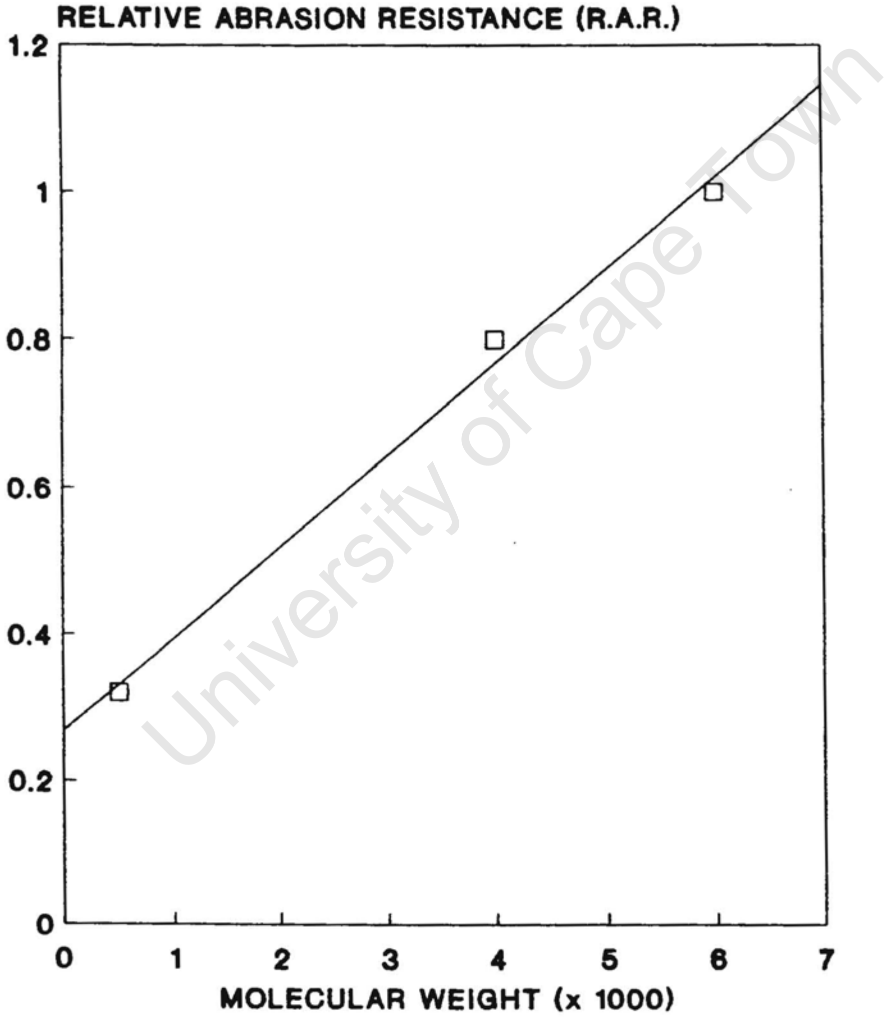


FIGURE 19 : MOLECULAR WEIGHT vs RELATIVE ABRASION RESISTANCE (R.A.R)

6.2.3 CERAMIC

The ceramic material tested was a 90% sintered Alumina. This material, even with its exceptional hardness, is susceptible to the effects of changes in particle shape and size of the slurry solids. This can be seen from the larger R.A.R. values at a slurry lifetime of 600 minutes, when the impacting particles are more rounded and smaller (see Table 5.2.).

The impact surface characteristics were too fine to be seen under the optical microscope and the specimen too large to fit into the S.E.M.. However there is essentially one wear mechanism for sintered Alumina, and that is cracking, either intergranular or transgranular (52).

CHAPTER 7

CONCLUSIONS

The following observations on the wear resistance of the materials tested are made:

1. No two families of materials have the same wear mechanism. This is due to the different structures of the materials, resulting in them reacting to impacting particles in different ways: ductile platelet formation in steels, roll formation in rubbers and cutting and gouging in polyurethanes. In this respect, if mild steel is to be used as a standard, R.A.R. values should be given for every change in the environment (changes in particle shape and size), as each material type is going to perform differently under different circumstances, and its wear resistance is going to change accordingly.

2. Particle degradation is a function of the pump and pipeline. Particle size in particular has a linear relationship with respect to time for this test procedure. However, due to the change in particle shape which is not possible to quantify, the results cannot be normalised to a fresh slurry condition at any particular slurry lifetime. Thus, it is necessary to give R.A.R. values for the different particle shapes relating to the particular slurry lifetime.

3. Metals with increasing hardness display increasing wear resistance, or alternatively, increasing the carbon content of metals increases their wear resistance.

4. Rubbers of increasing hardness display decreasing wear resistance. The resistance to wear is inversely related to the resilience of the material.

5. Polyester type polyurethanes have a greater wear resistance than polyether type polyurethanes, and their wear resistance seems to depend largely on tear strength and their mechanical properties.

6. Increasing the molecular weight of polyethylene increases its wear resistance.

7. A hierarchy, based on their wear resistance, exists in each group of materials and this remains unchanged, regardless of the angle of impact or the changing nature of the impacting particles.

8. This design of test rig has proven successful, in terms of reproducing results, speed of testing, and the ranking of materials under conditions of wet impact abrasion.

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APPENDIX 1

INSTRUMENTATION

VERTICAL COUNTER-FLOW METER

The vertical counter-flow meter can be considered as an inverted U tube. There are pressure tappings on the upward and downward sections at points 1,2,3 and 4, see figure 20, that measure the pressure difference between the two sections. By means of these pressure difference measurements in the upward and downward flowing sections, the slurry is weighed in these two sections and compared against each other. The pressure difference is measured using manometers attached to the pressure tappings by means of pressure hosing. The manometers, initially filled with water, are injected with a small quantity of air, under pressure, to balance the pressure emanating from the tapping. The two manometers relating to either the upward or downward tappings are joined in such a way that the air trapped in one manometer is allowed to expand into the adjoining manometer. The pressure of the air pushes the water in the manometers into an equilibrium relating to the pressures between the two tappings in either the upward or downward sections. The difference between the heights of the water, in equilibrium, in the two manometers relating to each section (either upward or downward) is the pressure difference between either points 1 and 2 or points 3 and 4, ΔH_{UP} or ΔH_{DOWN} respectively.

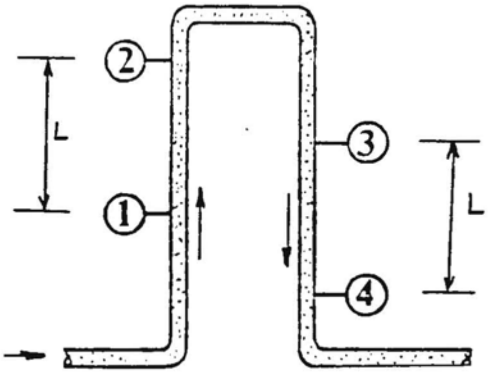


FIGURE 20: VERTICAL COUNTER-FLOW METER

The analysis used in calculating the concentration of solids in the slurry is complicated (27), but can be simplified to:

$$Smd = (\Delta H_{UP} - \Delta H_{DOWN} / 2L + 1)\ Swm$$

where:-

Smd = relative density of the slurry delivered
ΔHup = difference in pressure readings at 1 and 2
ΔHdown = difference in pressure readings at 3 and 4
L = the distance between the pressure tappings
Swm = the density of the water in the monometers

and

$$Cvd = (Smd - Swt / Ss - Swt)$$

where

Cvd = the volumetric concentration delivered
Swt = density of the water within the tank
Ss = density of the solids in the slurry

MAGNETIC FLOWMETER

The magnetic flowmeter is situated in the vertically downward section of the counter flow meter (Figure 1,[3]). It functions on the principle that the voltage induced across a conductor (the slurry), as it moves at right angles through a magnetic field, is proportional to the velocity of the conductor.
The result is given as a voltage signal in milli-amps.

$$\mathbf{E = K.D.B.Vm} \quad \text{and} \quad \mathbf{E} \propto \mathbf{Vm}$$

where

E = the voltage signal
K = constant
B = magnetic flux density
D = length of the conductor
Vm = flow velocity

The flowmeter is calibrated by taking weight measurements of the slurry transported over a period of time. To achieve this the weigh tank is used (see figure 1,[6c]).
With the weight of the slurry transported over a timed period and the area of the delivery pipe, a velocity for the slurry can be calculated. This velocity reading is related to the milli-amp reading achieved, and since a linear relationship exists between these two variables, a formula can be developed. The specific formula for this work is given below

$$\mathbf{V = 0.387.A}$$

where

V = the velocity
A = the amp reading

APPENDIX 2

RIG RUNNING OPERATIONS

These operating procedures must be read in conjunction with the schematic diagram of the rig given in figure 21.

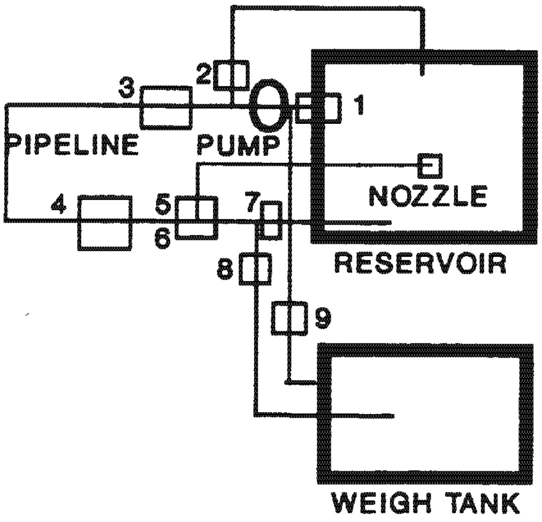


FIGURE 21: SCHEMATIC LAYOUT OF THE TEST RIGS CONTROL VALVES

START UP

1. The slurry reservoir is filled with a water/tailings mixture to give a 12% by volume concentration of solids.
2. The agitators are started to keep the solids in suspension.
3. Drop valve 2 is opened.
4. Ball valve 5 is opened, this simultaneously closes ball valve 6.
5. Gate valve 7 is opened.
6. Ball valves 3 and 9 are closed.
7. Drop valve 4 is closed.
8. Gate valve 8 is closed.
9. Sluice valve 1 is opened, opening the slurry reservoir to the centrifugal pump.

10. The pump is started. The slurry is now circulating through a return line operated by drop valve 2.
11. Ball valve 3 is opened, opening the actual pipeline to the pump, however flow through the loop can not occur because the return pipe is closed by drop valve 4.
12. Drop valve 4 is opened. This allows the slurry to flow though the loop, through ball valve 5, and to be jetted onto the specimen in the slurry reservoir.
13. Drop valve 2 is closed. This allows the slurry to circulate only in the closed loop pipeline, thus resulting in maximum pressure, velocity and solids throughput.
14. The cooling system and the air pressure supply is now switched on.
15. The ball valve bypass system is operated, using the air operated rotary actuator. This closes ball valve 5, simultaneously opening ball valve 6, returning the slurry to the slurry reservoir via a bypass line opened by gate valve 7, thus shutting the nozzle off while the specimen beneath it is changed.
16. The bypass system is operated in reverse returning the flow of slurry to the nozzle line.

USING THE WEIGH TANK (see Appendix 1)

17. Gate valve 7 is closed.
18. Gate valve 8 is opened.
19. When the ball valve bypass system is now operated, the slurry is diverted to the weigh tank.
20. To return the slurry diverted to the weigh tank, ball valve 9 is opened and the suction from the pump draws the slurry back into the closed loop pipeline.

SAMPLING THE SLURRY

21. The return line operated by drop valve 2 is unclamped from the slurry reservoir.
22. Drop valve 2 is opened an an aliquot of slurry diverted into a bucket.
23. Drop valve 2 is closed and the return line reclamped onto the slurry reservoir.

SHUTTING DOWN

24. The pump is switched off.
25. Ball valve 3 is closed as the flow of slurry slows, and the solids in the upward section of the counterflow meter start to settle. This is observed through a clear section of pipe connected directly after ball valve 3 to the counter flow meter.
26. Sluice valve 1 in the slurry reservoir is closed.
27. The Agitators, air supply and refrigeration unit are switched off.
28. Operations 3 to 8 are carried out.

APPENDIX 3

MINERALOGICAL ANALYSIS

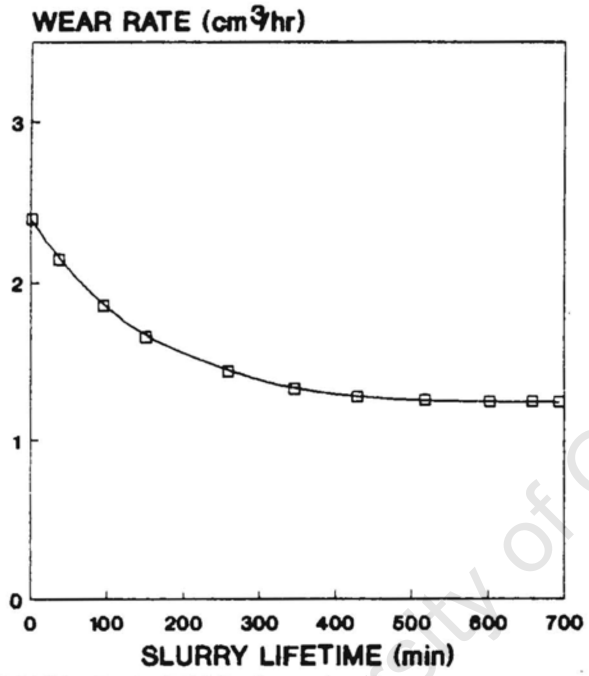
The tailings used as the solid component in this research was supplied by Rossing Mines of South West Africa, Namibia.

MINERAL	DESCRIPTION	HARDNESS Moh	FRACTION %
QUARTZ	TRANSLUCENT	7	35
FELDSPARS:			
PLAGIOCLASE			
ALKALI	MILKY WHITE	6-6.5	55
MICAS:			
BIOTITE	BLACK/RED	2.5-3	
CHLORITE	GREEN	2-3	7
ACCESSORY PHASES:			
APATITE	LIME GREEN	5	
PYRITE	GOLD	6-6.5	
ZIRCON	BROWN	7.5	3
SPHENE		5	
RUTILE	BLACK/BROWN	6-6.5	

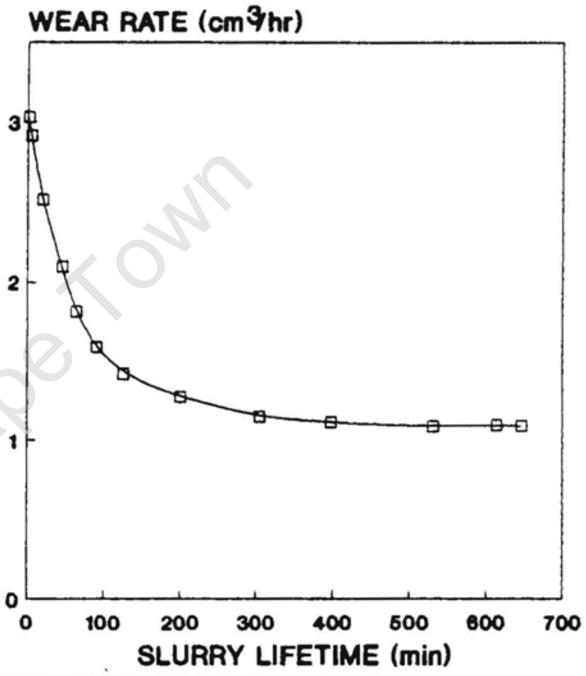
ANALYST: Mr.C.Hamilton, University of Cape Town

APPENDIX 4

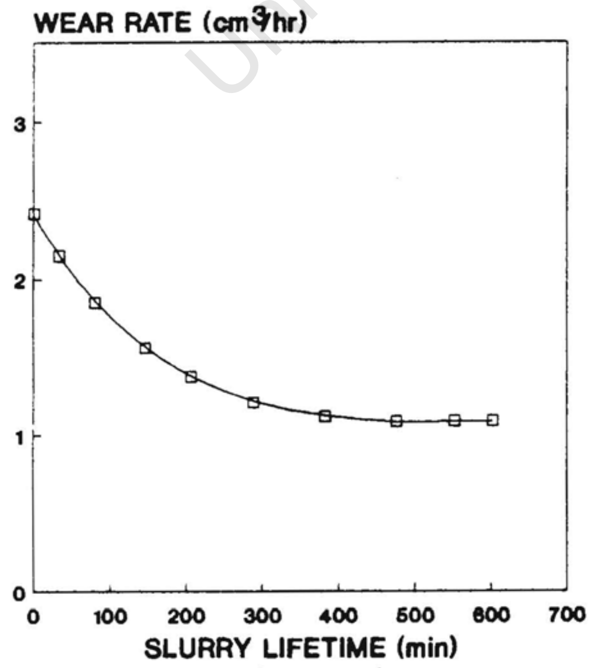
Graphs of slurry lifetime (minutes) against wear rate (cm^3/hour), for the materials tested at the three angles of impact, 20^0, 30^0 and 40^0.



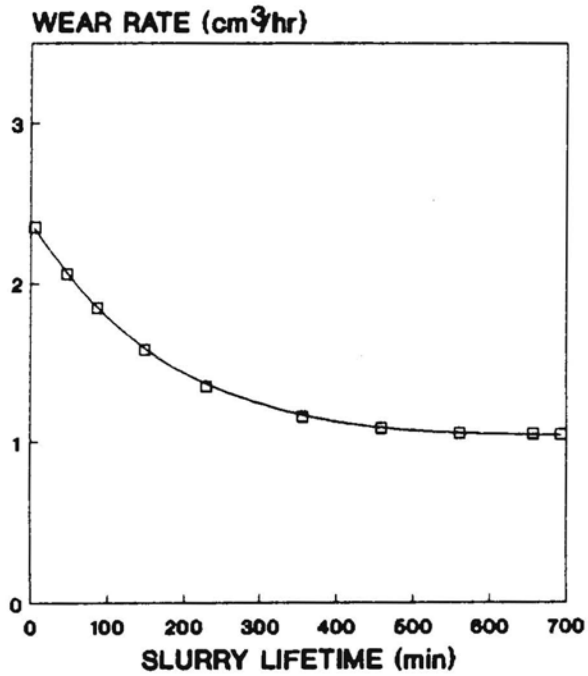
BRIGHT MILD STEEL (standard)
20 degree impact



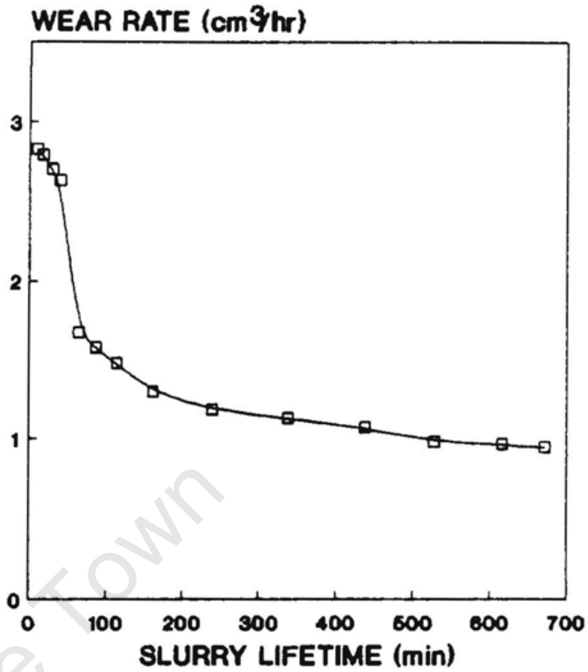
BRIGHT MILD STEEL (standard)
30 degree impact



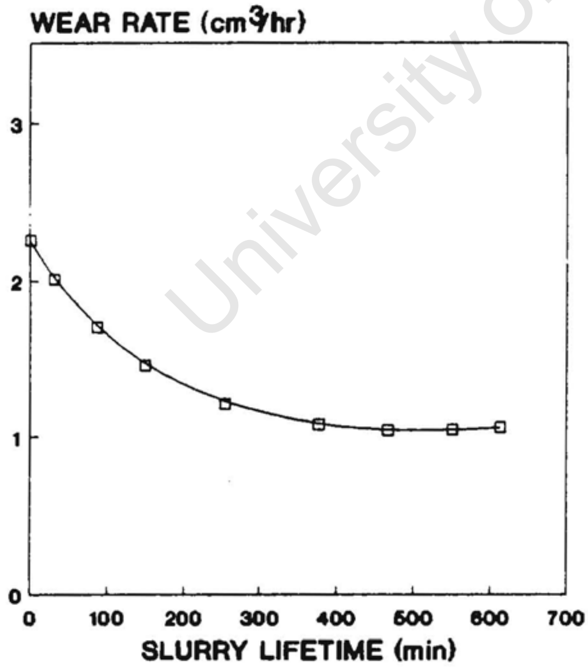
BRIGHT MILD STEEL (standard)
40 degree impact



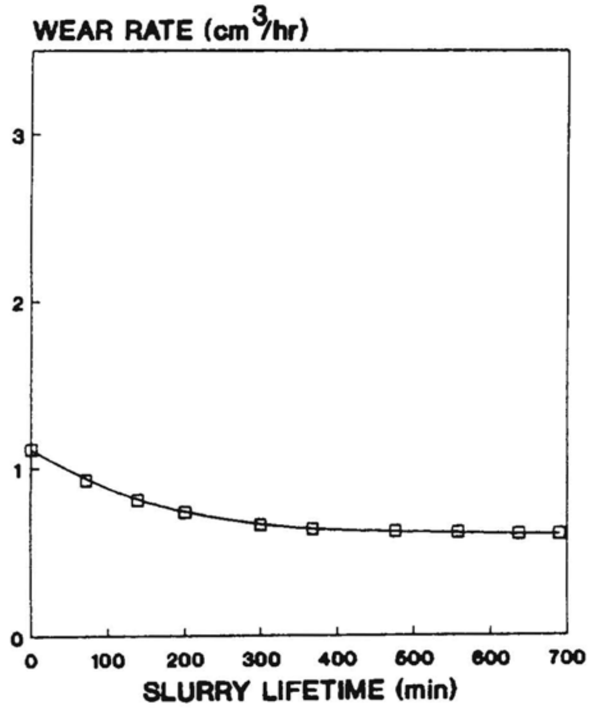
BLACK MILD STEEL
20 degree impact



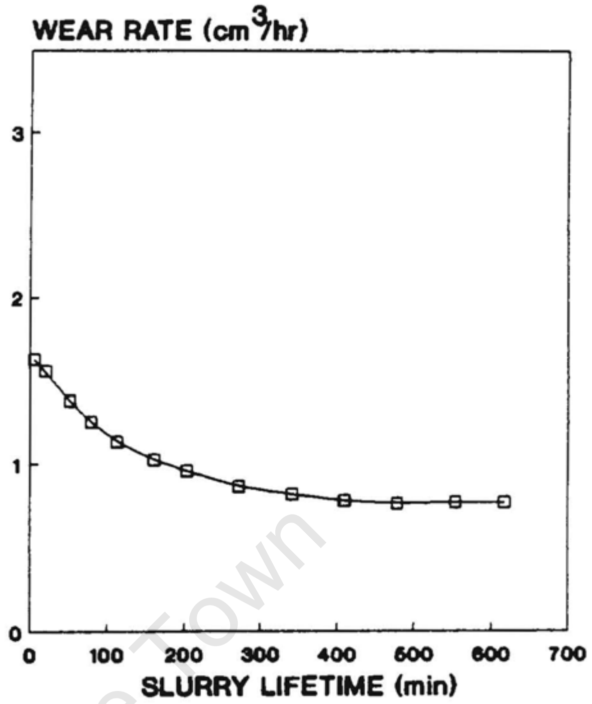
BLACK MILD STEEL
30 degree impact



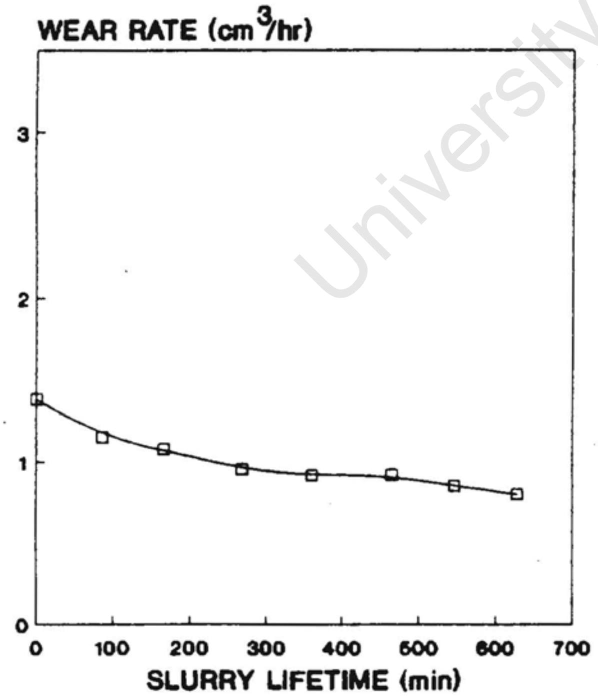
BLACK MILD STEEL
40 degree impact



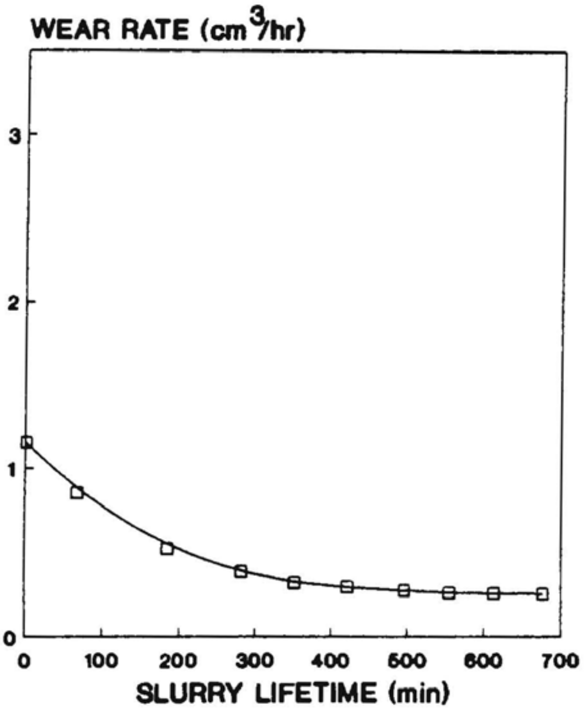
En24
20 degree impact



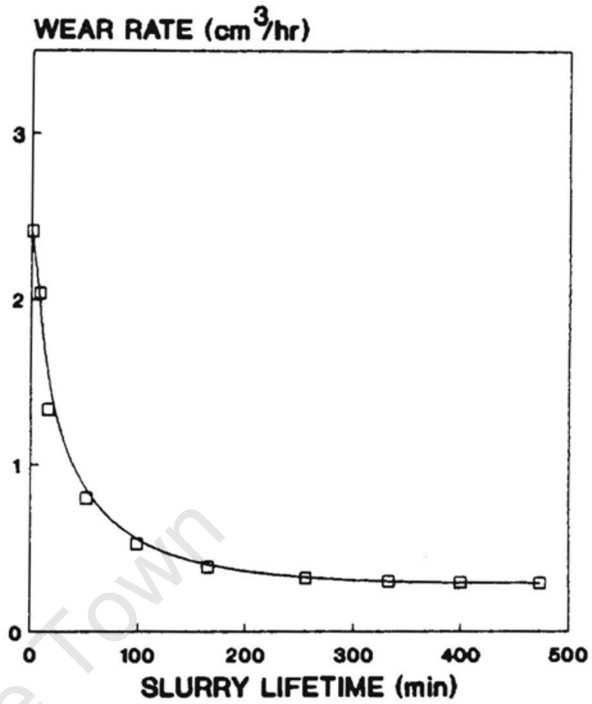
En24
30 degree impact



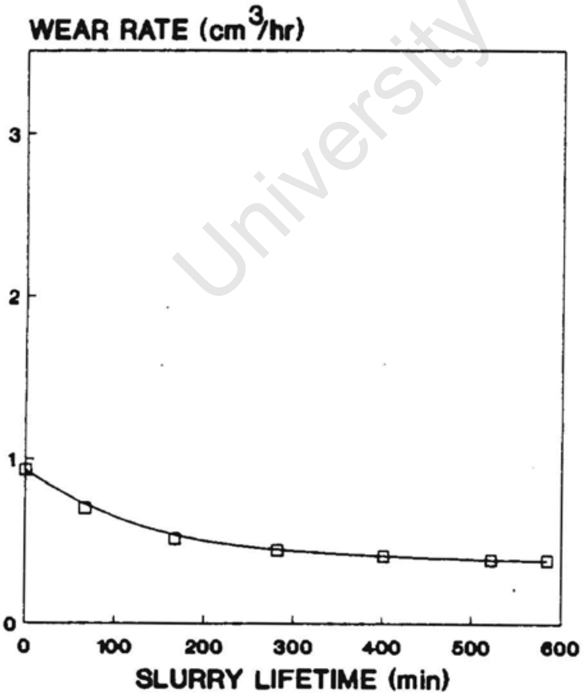
En24
40 degree impact



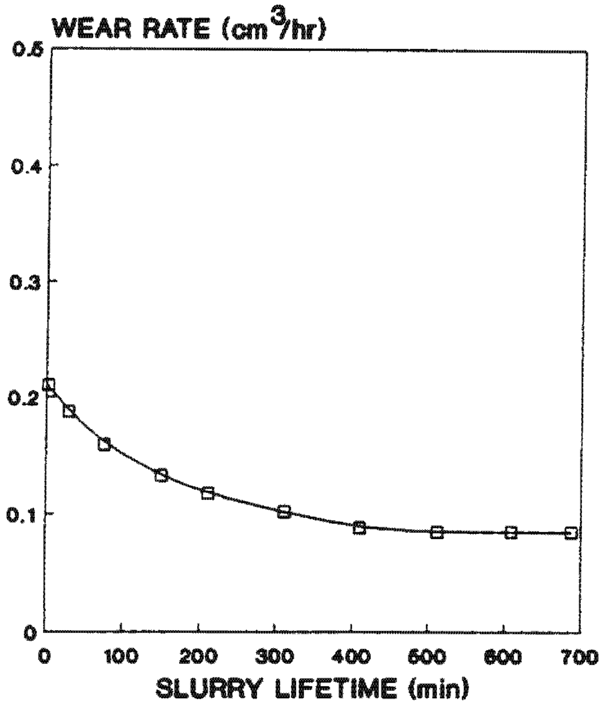
AUSTEMPERED DUCTILE IRON 1
20 degree impact



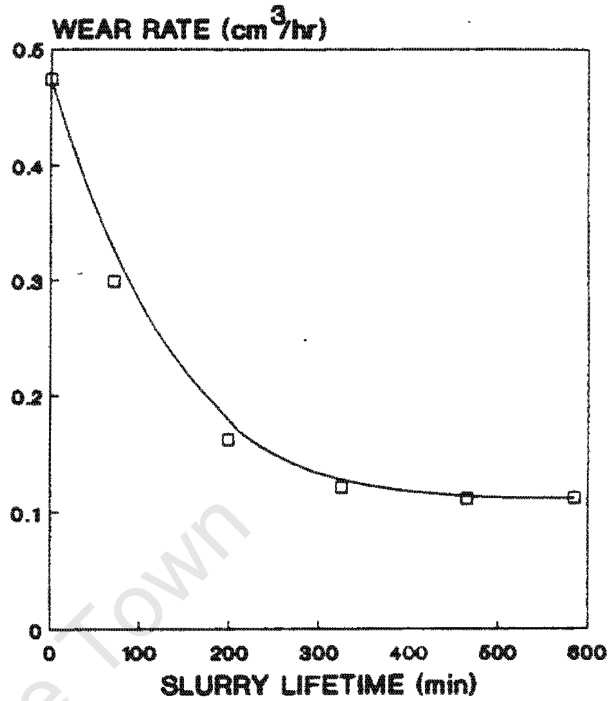
AUSTEMPERED DUCTILE IRON 1
30 degree impact



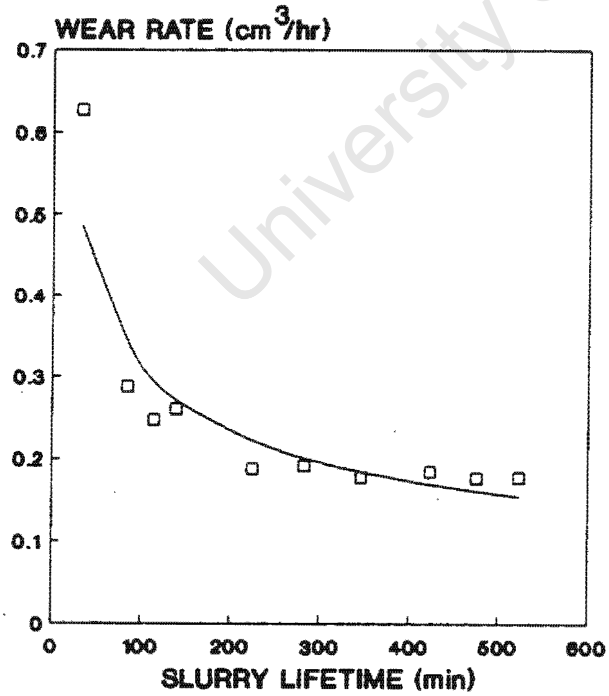
AUSTEMPERED DUCTILE IRON 1
40 degree impact



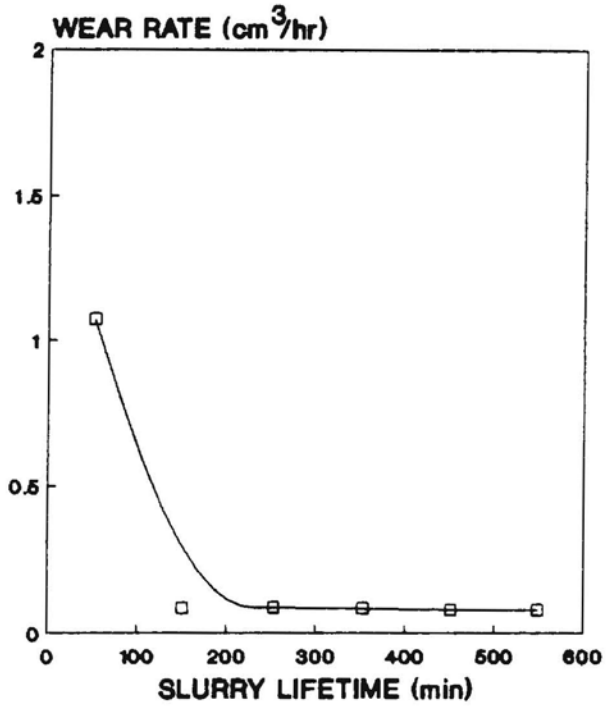
HIGH CHROMIUM WHITE CAST IRON
20 degree impact



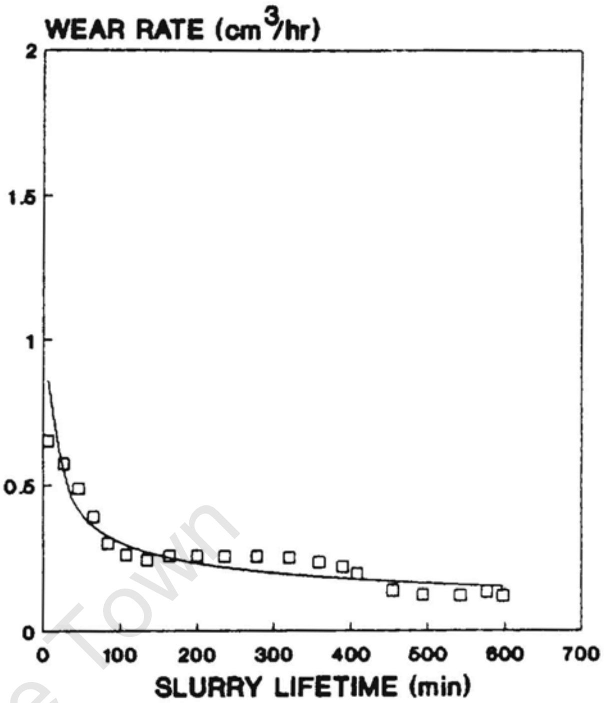
HIGH CHROMIUM WHITE CAST IRON
40 degree impact



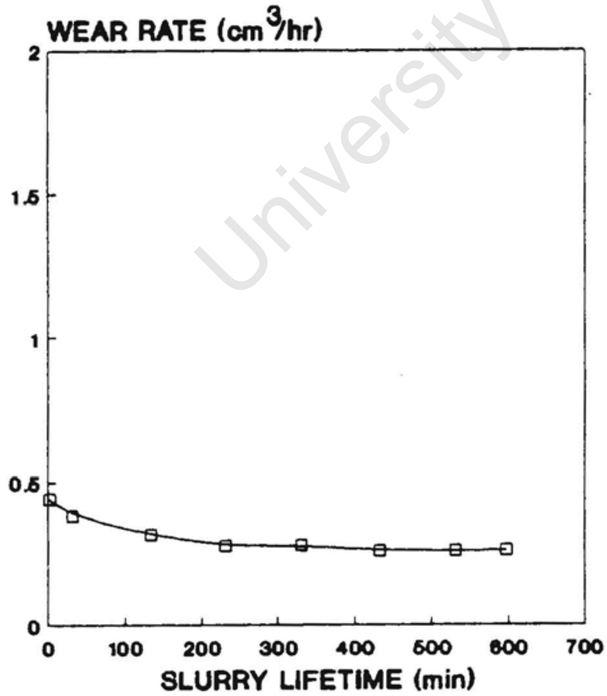
HIGH CHROMIUM WHITE CAST IRON
30 degree impact



SINTERED ALUMINA
20 degree impact



SINTERED ALUMINA
30 degree impact



SINTERED ALUMINA
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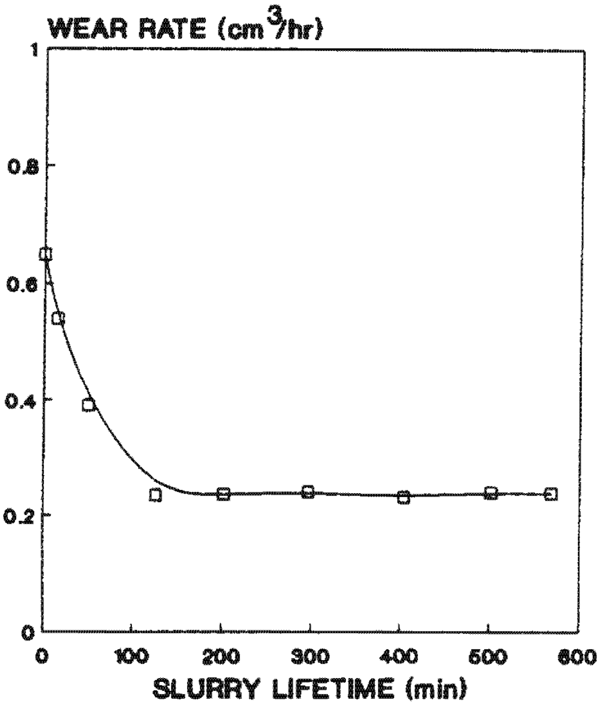
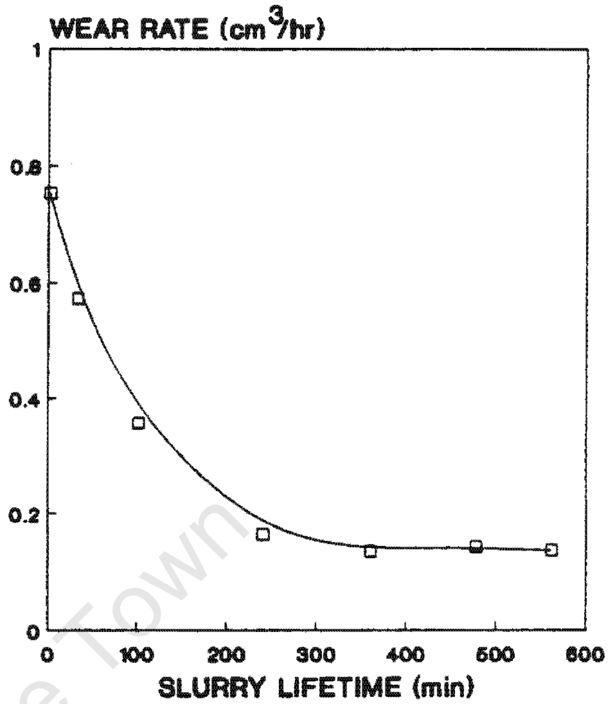
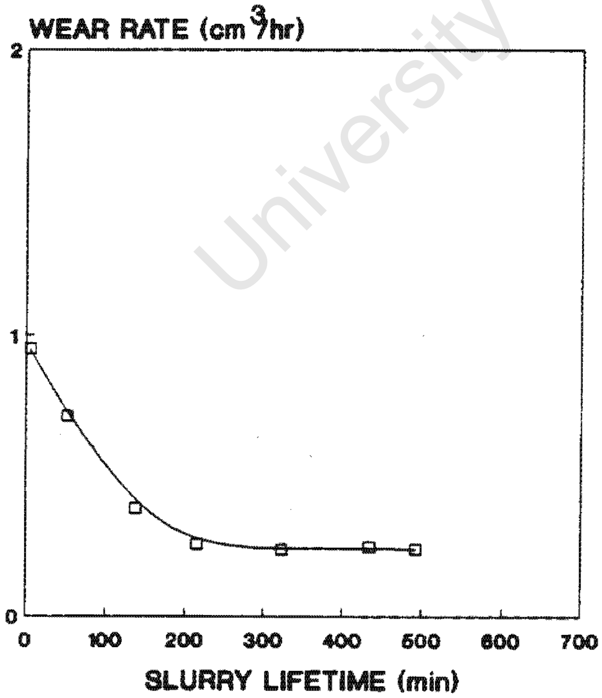


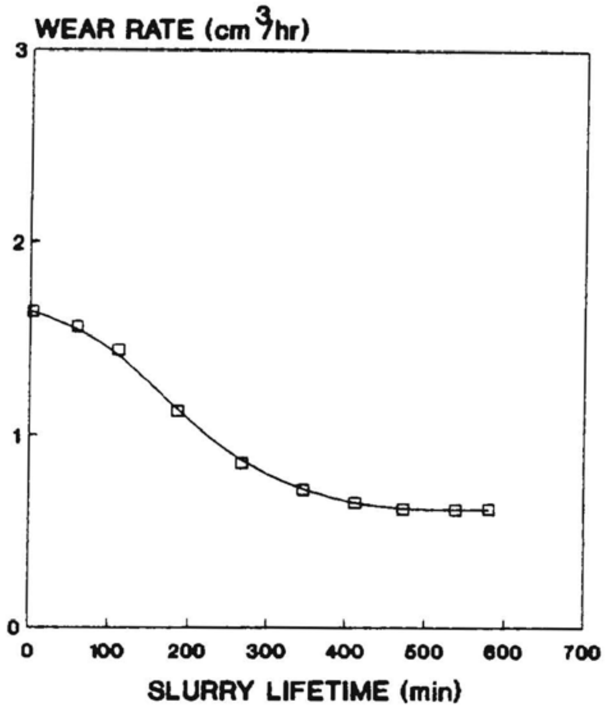
VULKOLLAN
20 degree impact



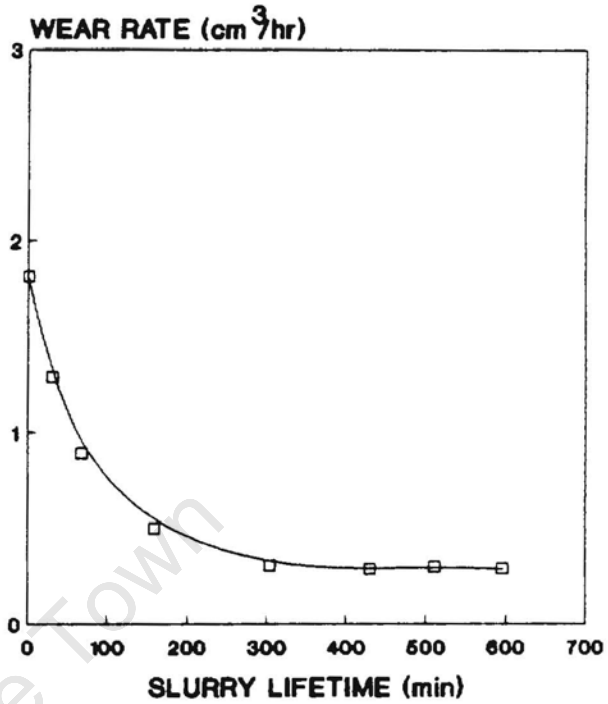
VULKOLLAN
30 degree impact



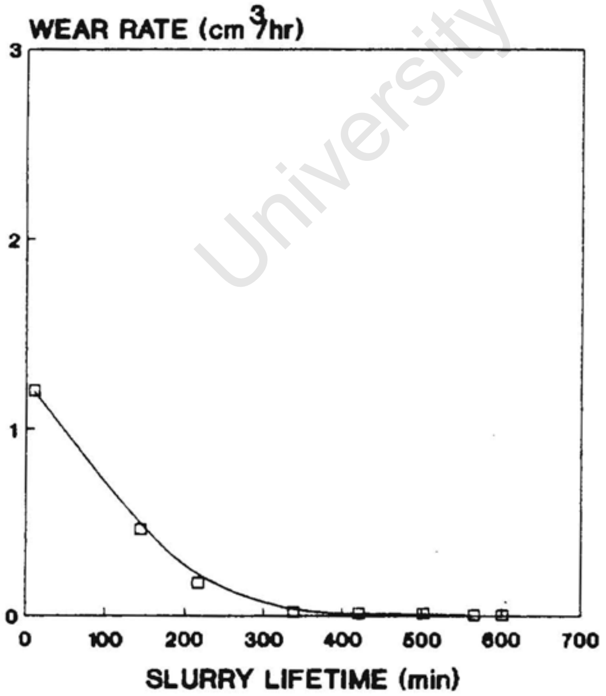
VULKOLLAN
40 degree impact



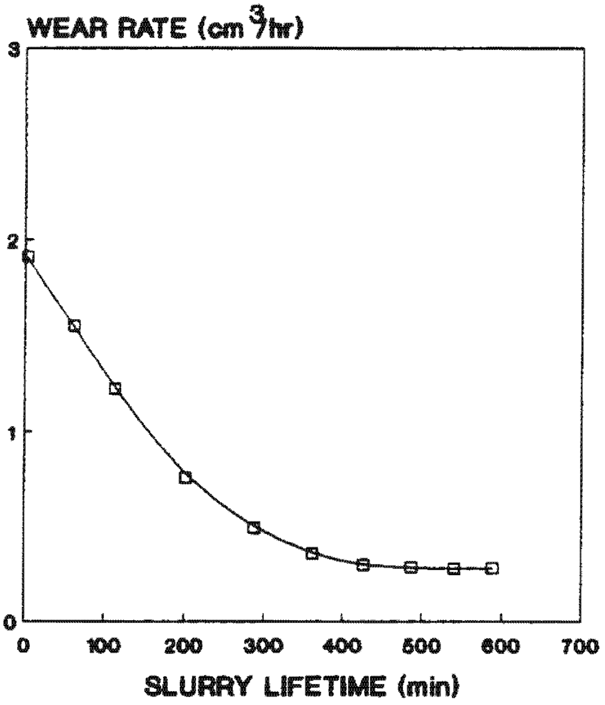
POLYETHER 1
20 degree impact



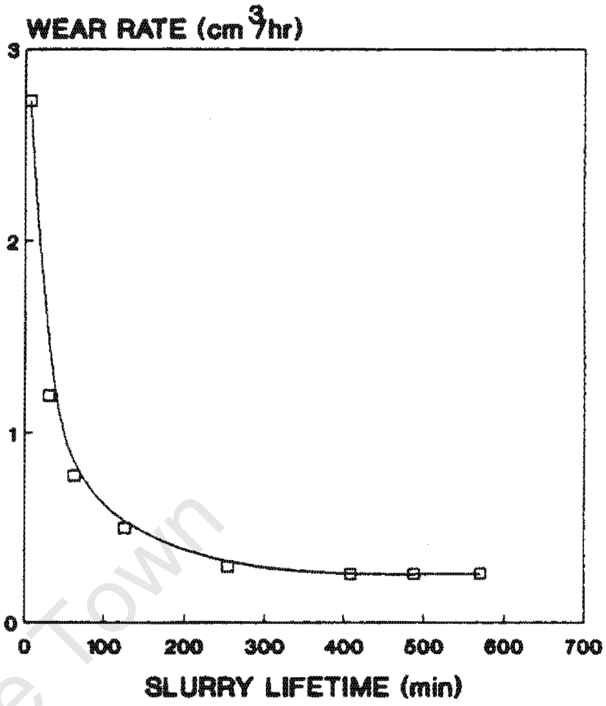
POLYETHER 1
30 degree impact



POLYETHER 1
40 degree impact



POLYETHER 2
20 degree impact



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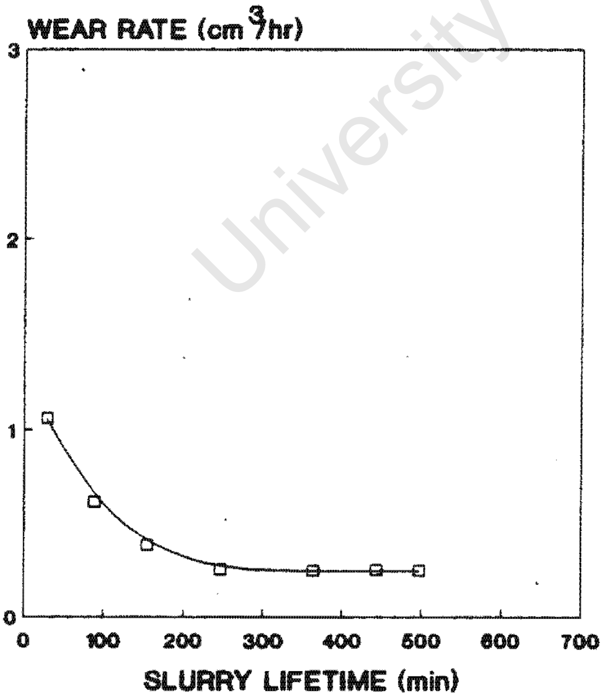

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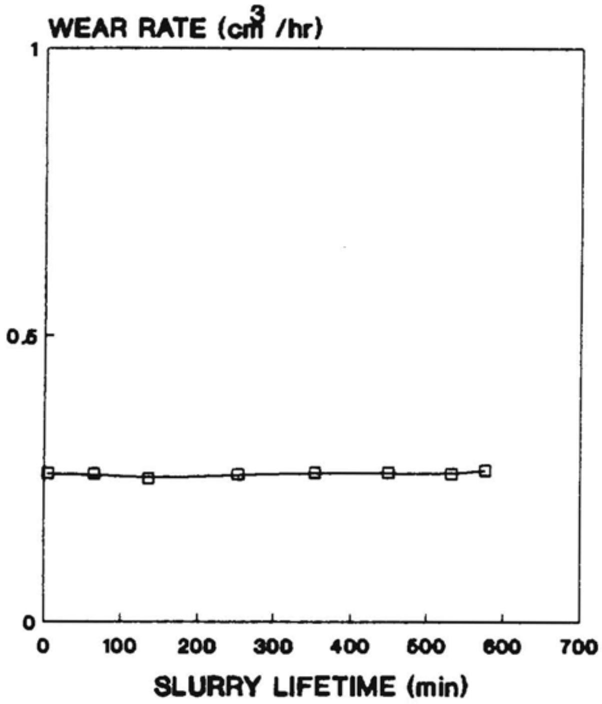
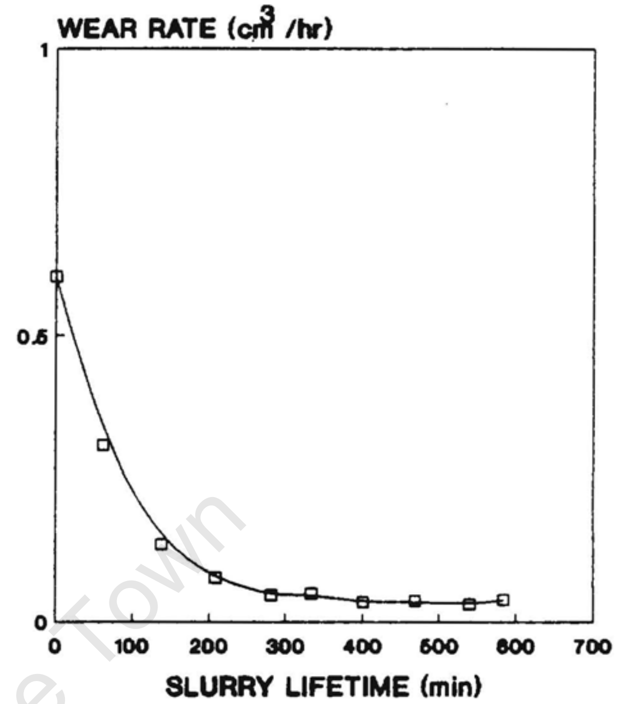
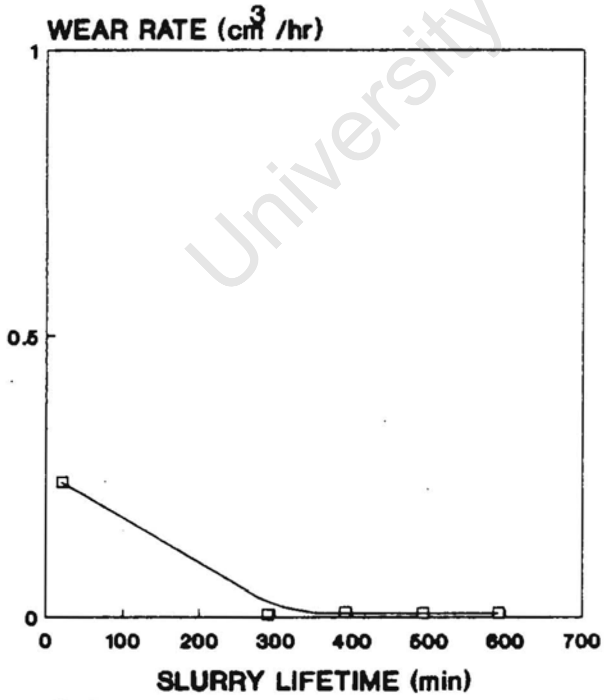


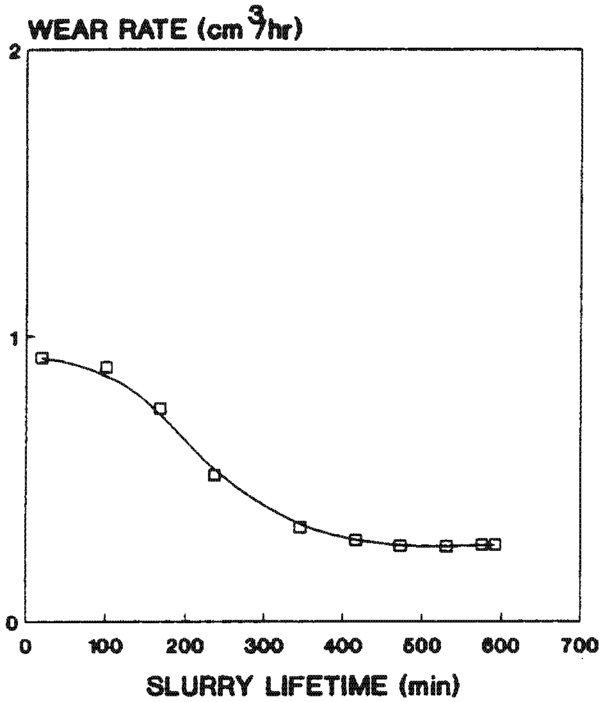
POLYESTER 1
20 degree impact



POLYESTER 1
30 degree impact



POLYESTER 1
40 degree impact



POLYESTER 2
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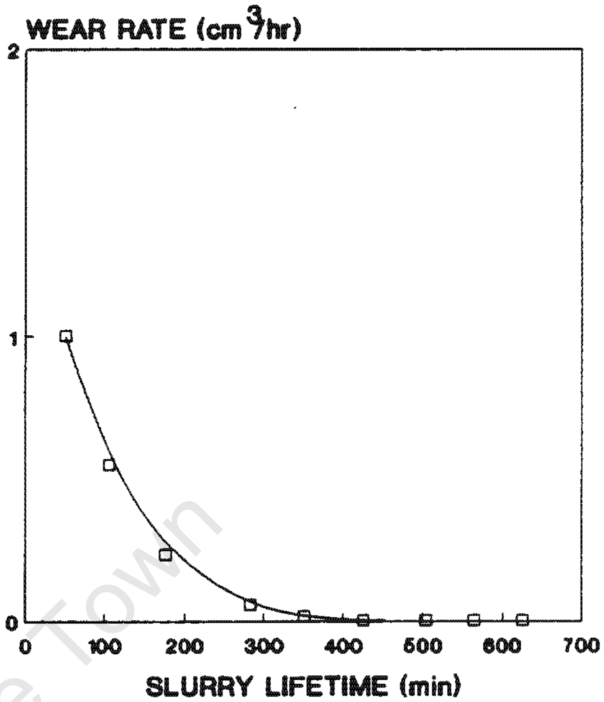
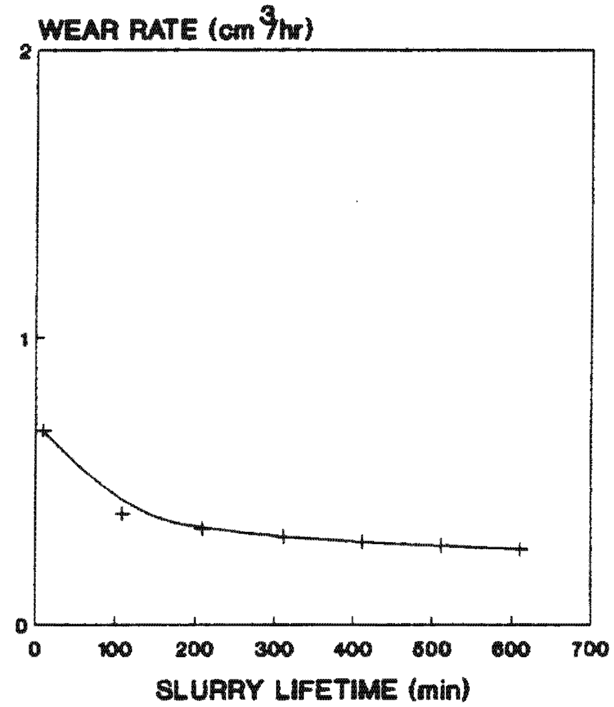
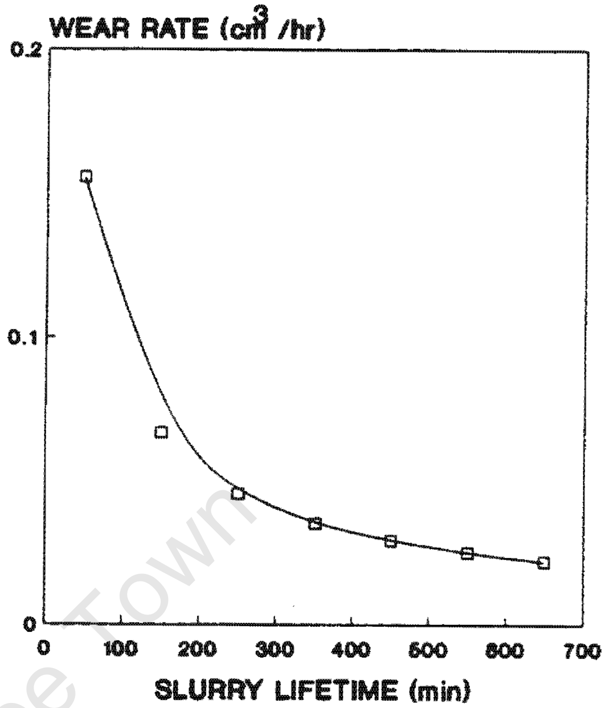


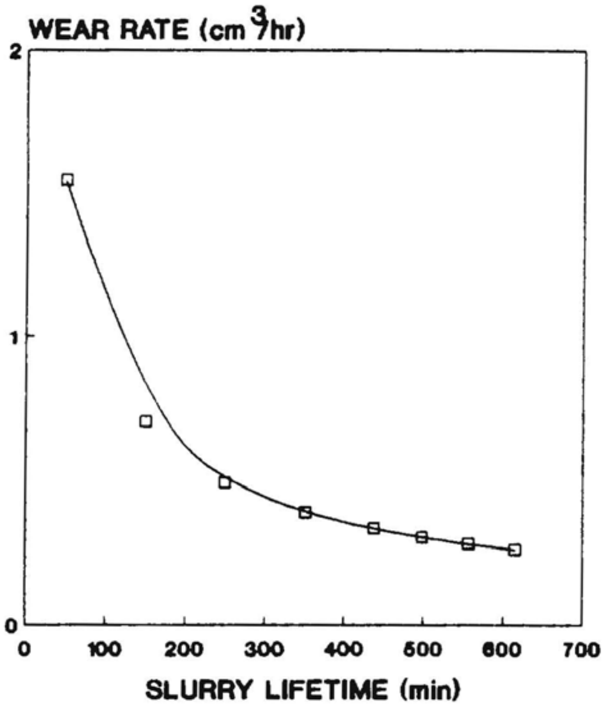
POLYESTER 2
40 degree impact



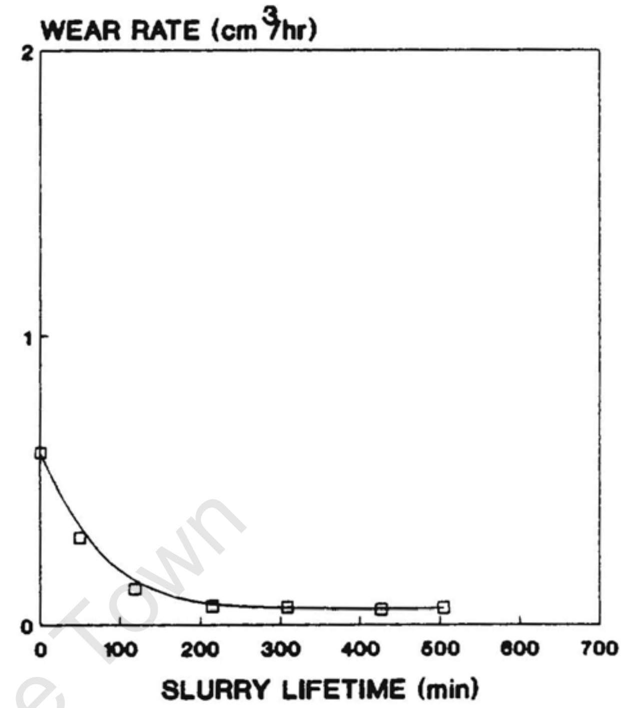
LINATEX
20 degree impact



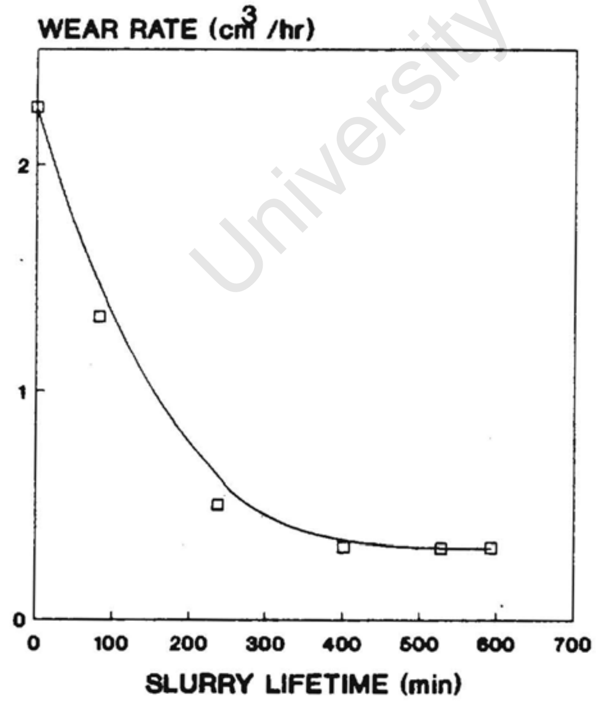
IR
20 degree impact



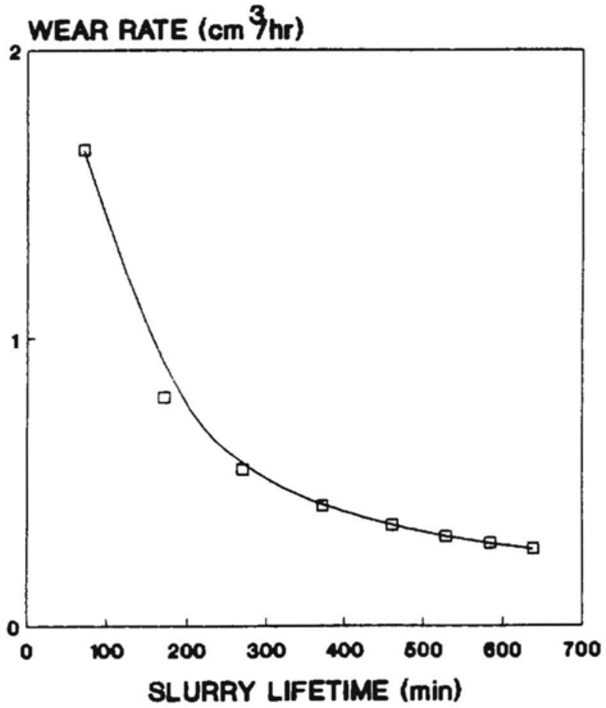
R1
20 degree impact



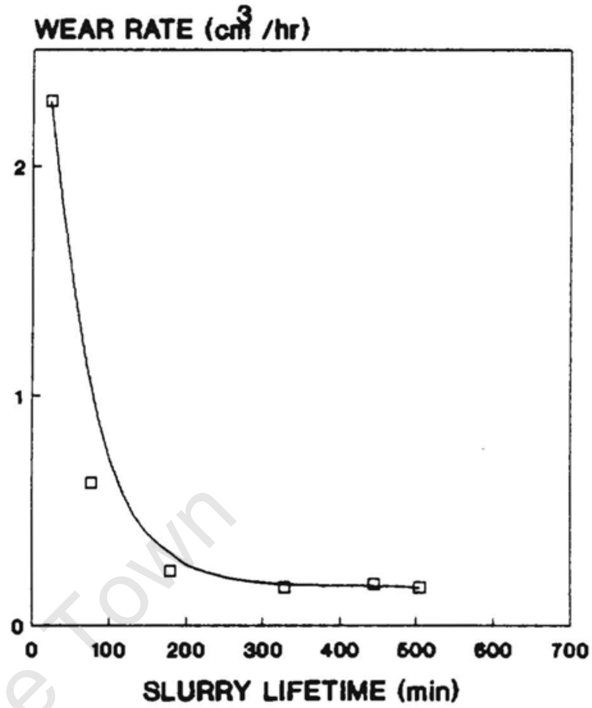
R1
30 degree impact



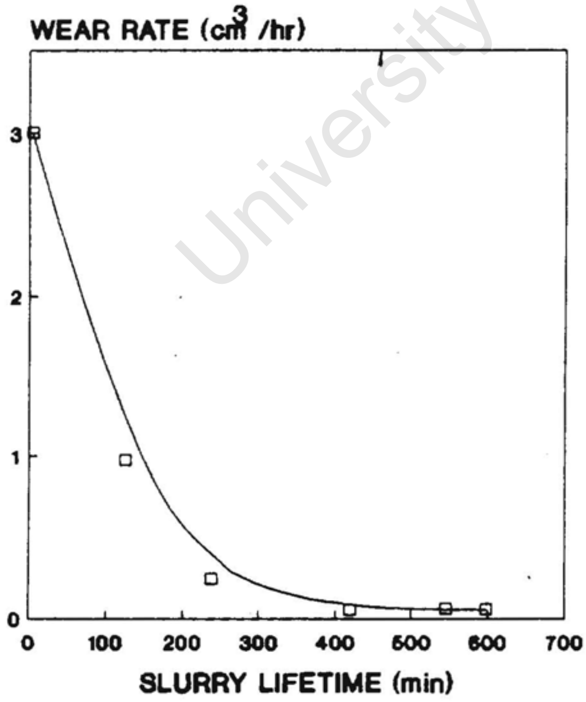
R1
40 degree impact



R2
20 degree impact



R2
30 degree impact



R2
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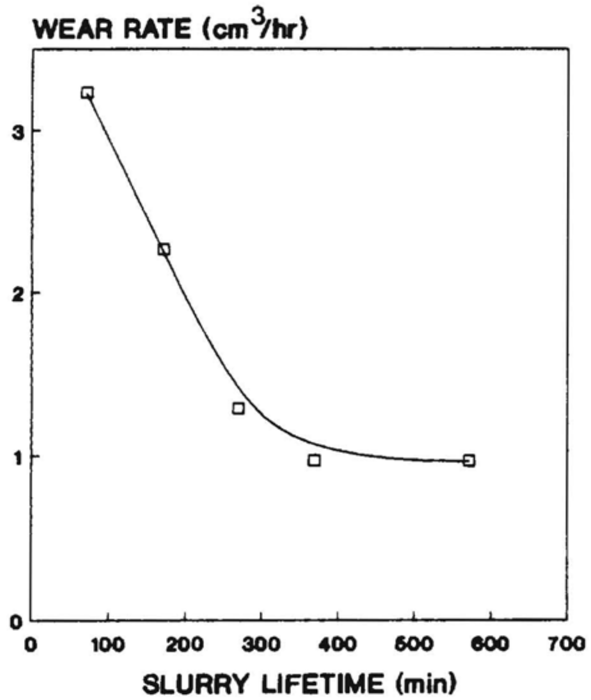
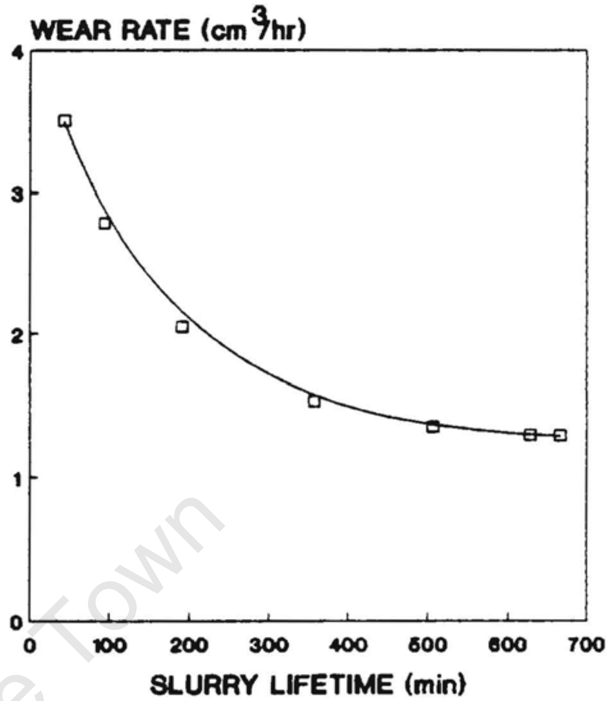


P2
20 degree impact



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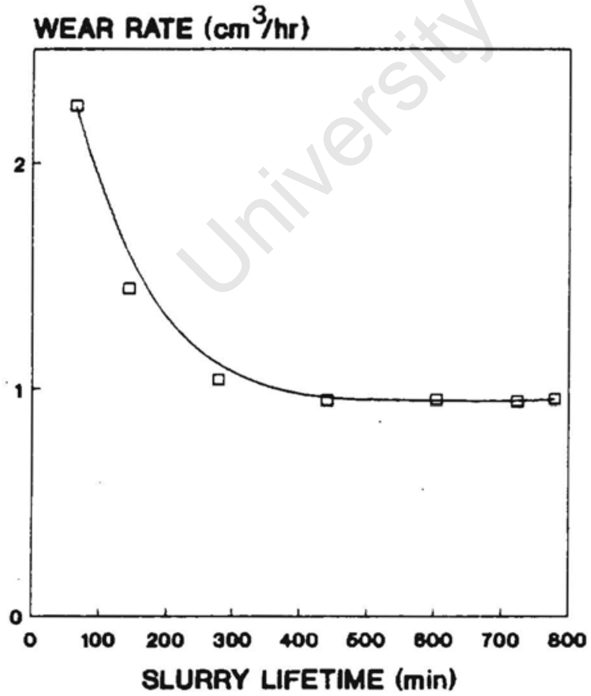

P2
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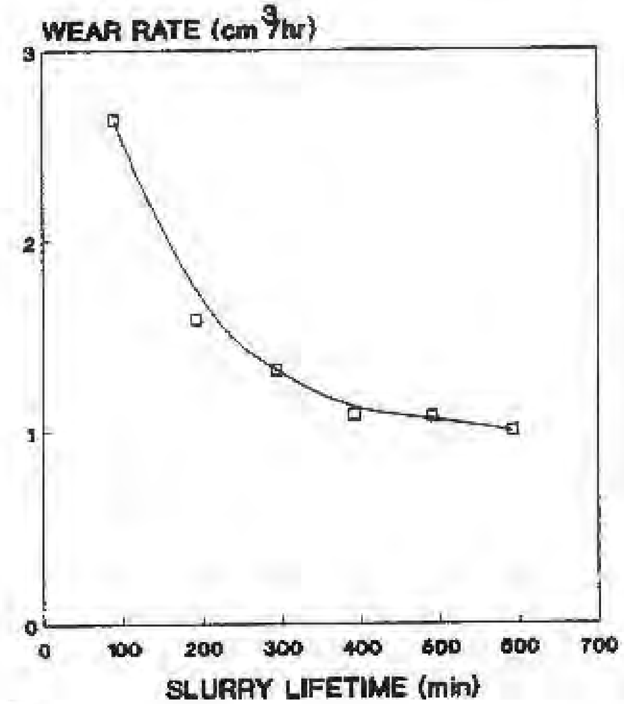
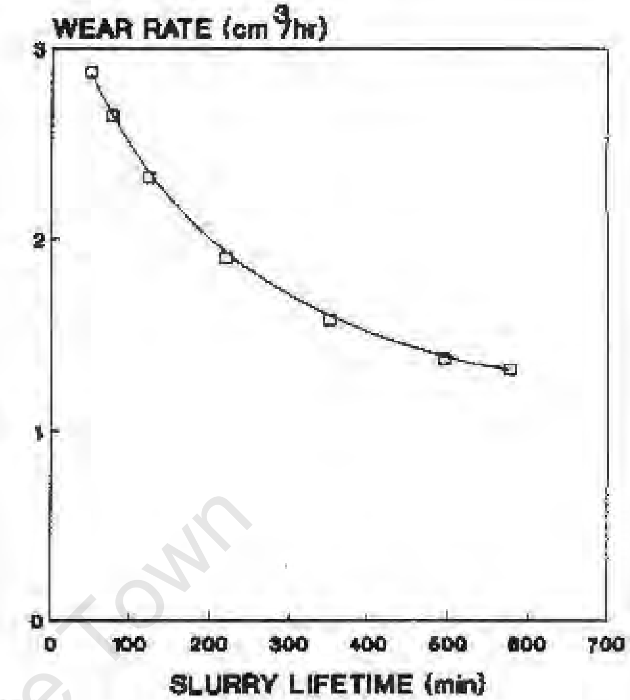
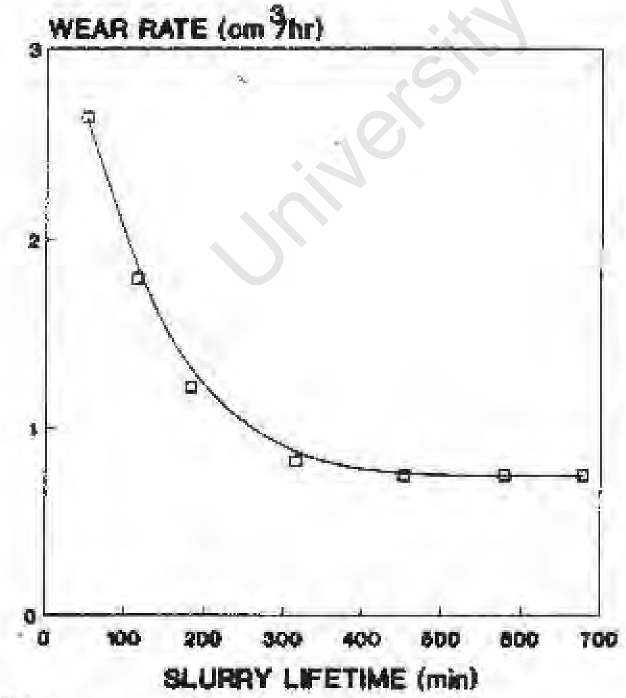


P4
20 degree impact



P4
30 degree impact



P4
40 degree impact