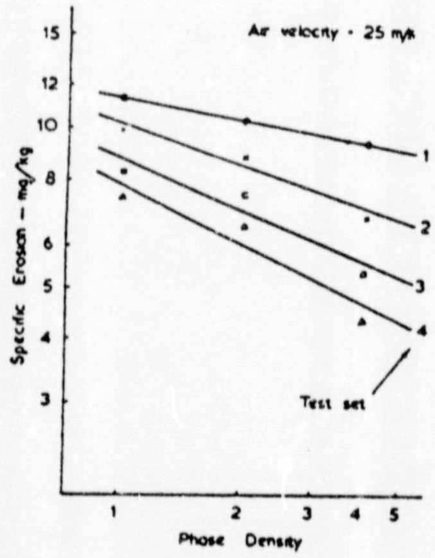

Figure 7. Variation of erosion with phase density for 230 micron sand. (After Mills and Mason, 12).

The result here was a change in slope, as well as an overall decrease in erosion for each set of tests. The slope changed from about -.16 to -.38. Thus the final result for the 230 micron sand was very close to the result obtained for the 70 micron sand. From this it would appear that the condition of the conveyed product has a significant effect on the variation of erosion with phase density.

Erosion results obtained from bench top tests have generally shown that specific erosion decreases only very gradually with increase in phase density. This tends to confirm the above result for the least worn 230 micron test, as normally in bench top tests fresh abrasive powders are used.

Particle size has been shown to have little effect on the variation of specific erosion over this range of phase densities, and therefore some other material property must be responsible for this rapid decrease in erosion with respect to time (most probably particle shape or sharpness).

Effect of impact angle

It has been found (10,13) that for the erosion of ductile materials there are three characteristic curves, as the following graph shows:

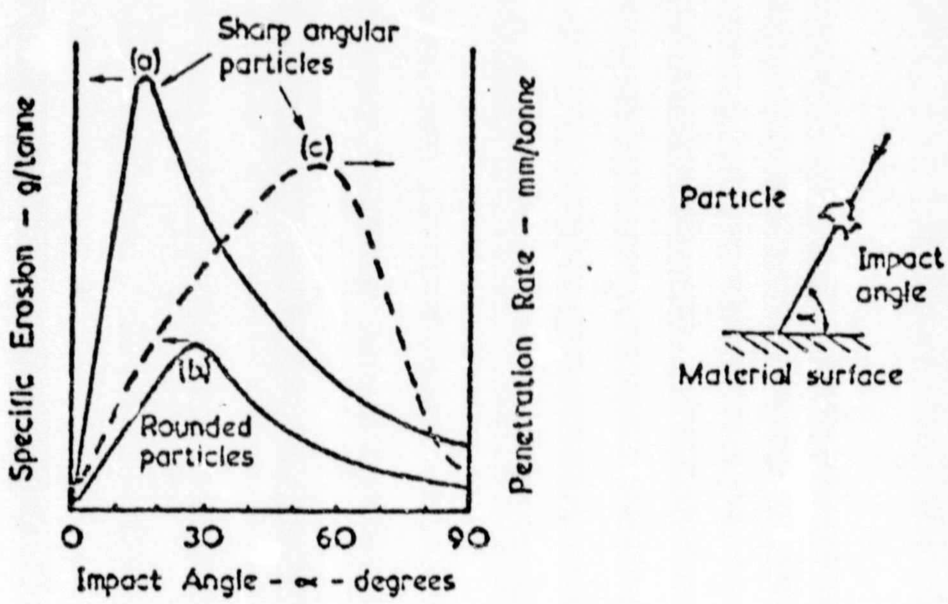

Figure 8. Influence of impact angle on erosion. (After Mills and Mason, 9)

Curve (a) is typical of the results obtained with sharp angular particles, with maximum mass eroded occurring at an impact angle of about 16°. curve (b) is typical of spherical or well rounded particles, with maximum mass eroded occuring at an angle of about 28°. Curve (c) is drawn on a basis of particle penetration rate instead of mass eroded, and this shows that for angular particles the maximum occurs at an impact angle of about 60°. All three curves show that very little erosion takes place under normal impact with ductile materials.

It has been suggested by Mills and Mason (9), that the difference in the effects of both particle shape and size can be explained by the difference between these maximum erosion values. In terms of the particle size, with large particles the maximum impact angle only reaches about 50° at the point of failure. With small particles, steps and ridges form which create a completely different eroded surface, and therefore the whole range of impact angles are present. The maximum depth of penetration, therefore, is soon reached and the bend fails with only a small mass eroded from a concentrated area on the bend wall surface.

Effect of particle size

For the erosion of metal surfaces it appears that there is a critical particle size above which specific erosion is not influenced by size and that this increases with velocity. In pneumatic conveying velocity ranges, Mills and Mason (9) indicate that specific erosion should increase to a maximum at a particle size of about 50 microns and then remain constant at that value with further increases in particle size. Particle size is a variable where there is scatter in the results, and hence can be a contributing factor to premature failure.

Figure 9, which is a plot of penetration rate against particle size, indicates that bends through which fine powders are conveyed will fail in a much shorter time than those through which larger particles are conveyed. It also shows that above a particle size of about 130 microns, the effect of particle size becomes less dramatic.

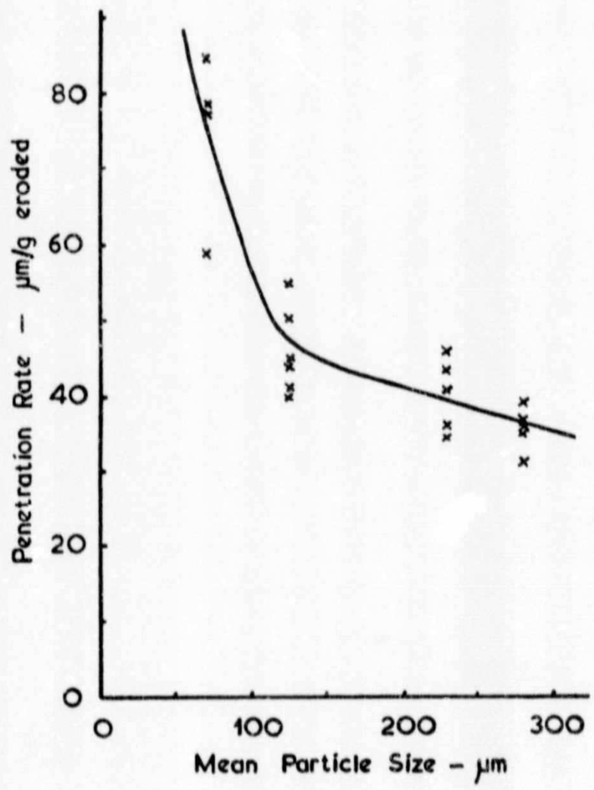

Figure 9. Variation of penetration rate with particle size. (After Mills and Mason, 14).

It has been established (14) that as the particles degrade and become less sharp and angular, the mass eroded decreases, but the penetration rate increases. In this case, however, the decrease in mass eroded has an overriding effect.

Effect of particle shape

It is generally accepted (6) that sharp, angular particles will cause more erosion than rounded particles in the case of specific erosion.

Effect of moisture content

Kleis (15) found that there was a rapid increase in specific erosion for a small initial increase in moisture content, but further moistening had little additional effect. The specific erosion increased by a factor of about two for sand particles with a moisture content of about 1% as compared with dry sand.

Effect of particle hardness

It is considered that erosiveness is a function of hardness of the impacting particles. Tilly (16) measured the Vickers microhardness of the particles as well as the erosiveness of a number of natural and industrial materials having hardnesses varying over an order of magnitude.

He found that the resulting erosion (figure 10, Pg 31) is related to hardness by the following expression:

$$\text{Erosion} = \text{const} \cdot H^{2.3}$$

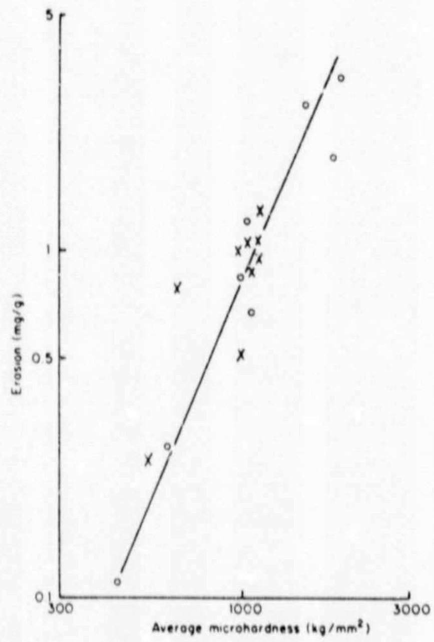

Figure 10. Effect of particle hardness on erosion. 125-150 micron particles against an 11% chromium steel at 130 m/s and 90° impact angle. (Circle = industrial material, cross = natural sand. After Tilly, 16).

Effect of bend radius

It has generally been recommended that the bend radius should be fairly large in order to reduce the effect of erosion. Work done by Mason and Smith (17) on long radius bends (100 mm nominal bore, 90° mild steel 1.37 m in radius), has shown that the erosion resistance of different materials changes as the angle of impingement changes.

They found that when the particles are harder than the bend material, rapid erosion occurs at low angles of impingement, 15° to 30°. The rate of wear at this primary wear point decreases as the impact angle increases i.e. as a pocket or hole is developed, until no further measurable increase in erosion occurs for impact angles between 80° and 90°.

The change in flow pattern induced by this pocket can result in erosion of the inside surface over an area of 30° to 60° bend angle, the peak wear occurring at approximately 40° to 45°. A secondary wear zone gradually develops on the outside surface and the peak wear occurs at a bend angle of about 70°. This secondary wear point can exceed the magnitude of the primary wear point.

Marcus (1), has investigated the performance of tee bends devoid of any radius, in the pneumatic conveying of dried slimes. It was found that initially high pressure losses resulted when material was stowed, but that once fine material had impacted in the dead area of the bend, the pressure drop decreased. Only slight evidence of erosion occurring on the outlet pipe was observed after 750 tons had been conveyed. Although these tests were not carried through to completion, cost factors involved in the manufacture of tee bends make this type of bend an attractive proposition.

2.3.5 Eroded material Characteristics

Surface hardness

Surface hardness is the single parameter most often chosen to describe ductile material erosion rate variations. Within one alloy however, indentation hardness is frequently not a valid parameter to describe erosion differences. Ruff et al (6) notes that dynamic hardness is probably the more appropriate variable for characterising the erosion of either ductile or brittle materials.

Toughness

Because materials erode by elastic - plastic processes, the dynamic toughness (dynamic K_c) plays an important role. Measurements of dynamic K_c are needed, both to rank materials and to develop a better understanding of the process of erosion.

The following two sections give an understanding of the properties and erosion of tungsten carbide so that the erosion of tungsten carbide can be seen in the context of the erosion of pipe bends.

2.4 Mechanical Properties of Tungsten Carbide

2.4.1 Introduction

To interpret the results of the erosion of tungsten carbide, a discussion of the mechanical properties of tungsten carbide is pertinent.

Tungsten carbides or sintered carbides, are products of powder metallurgy (18). They are made of finely divided, hard particles of carbide of refractory material, sintered with one or more of the iron group (Fe, Ni, or Co), usually cobalt, forming a material of high hardness and compressive strength. The hard constituents are tungsten carbides, usually in combination with lesser amounts of other carbides.
The carbides are present as individual grains, and also as a finely dispersed network resulting from the precipitation during cooling of carbides dissolved in the cobalt during sintering.

2.4.2 Effect of Cobalt content

After solidification the cobalt is present in the interstices as almost pure metal with its original ductility. Solid cobalt dissolves only about 1% of tungsten carbide at low temperatures. It is this low solubility of tungsten carbide, coupled with its ability to retain ductility, which accounts for the use of cobalt as the binder metal, as opposed to nickel or iron. The higher solid solubility of carbide in iron or nickel would result in a more brittle binder phase, which is undesirable.

The cobalt also has the ability to wet the carbide at elevated temperatures, which is important during sintering. This high wettability also means that the particle-matrix interfaces are not an easy fracture path (19).
Cobalt also has a very high work hardening capability as well as good corrosion and creep resistance.
The cobalt content is the most important variable in producing cemented tungsten carbides of different qualities. Cemented carbides for technical applications generally contain from 5 to 25 wt% (8.5 to 32 vol%) cobalt. The effect of cobalt on the mechanical properties of WC-Co materials is summarised in figure 11.

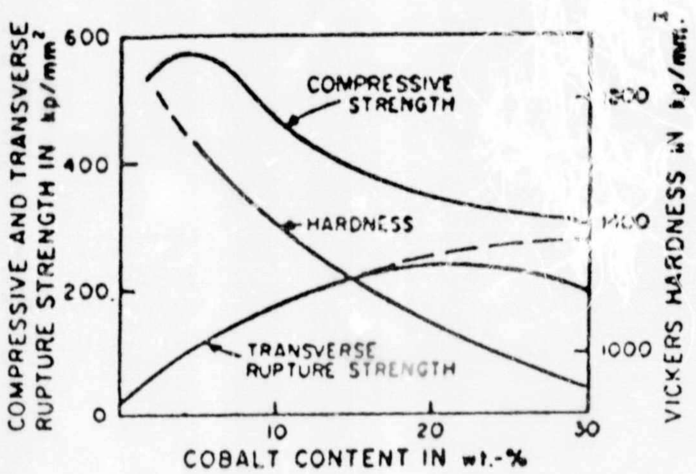

Figure 11. Effect of cobalt content on the mechanical properties of the tungsten carbide-cobalt alloy. (After Exner and Gurland, 21).

The hardness decreases in this range with increasing cobalt content and the compressive strength reaches a maximum at 5% and then drops sharply when the cobalt content is raised. The exceptional tool performance of tungsten carbides and hence its wear resistance, results from its high hardness and compressive strength. The lowest hardness of tungsten carbide is approximately the same as the highest hardness available in tool steel, Rockwell A 85 (± rockwell C 63), and ranges to Rockwell A 93, depending on the grade (18).
The transverse rupture strength, (TRS), which is a measure of tungsten carbide's resistance to fracture, improves with cobalt content up to a maximum at about 20% cobalt content. The maximum strength composition depends strongly on other variables as well such as the carbide grain size. The effect of carbide grain size is to decrease the compressive strength.

2.4.3 Microstructural Features of Tungsten Carbide

Figure 12, Pg 37, illustrates schematically the microstructural parameters of the WC-Co alloy (20).

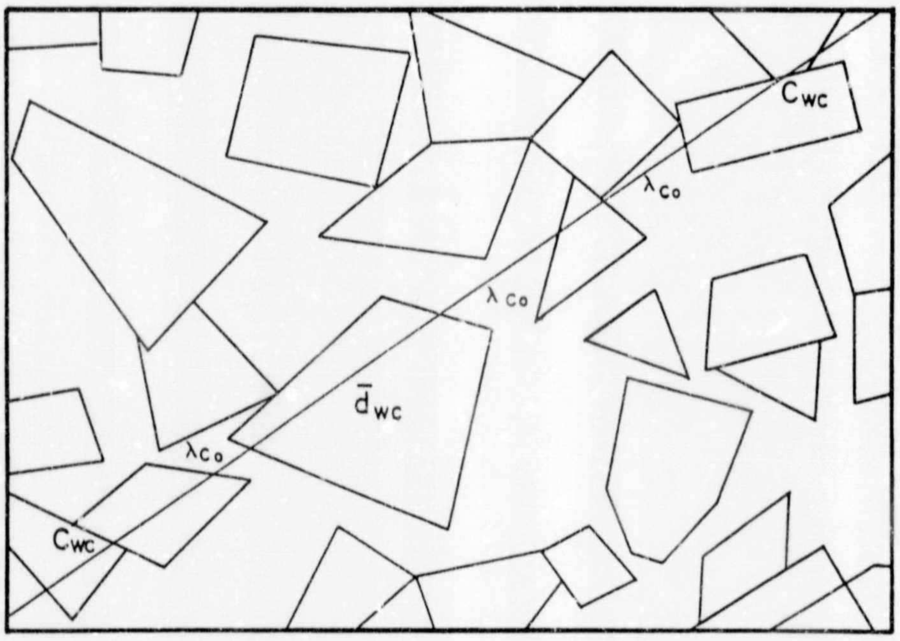

Figure 12. A schematic representation of the WC-Co alloy illustrating the microstructural parameters, where λ is the mean free path of the binder phase, $\bar{d}_{WC}$ is the tungsten carbide grain size and C is the contiguity. (After Pennefather, 20).

Mean Free path

The mean free path (figure 12) is a measure of the thickness of the cobalt layers and depends on both the cobalt content and the particle size. In the literature on tungsten carbides it is used as the single most important parameter characterising the microstructure.

Contiguity C_{WC}

The contiguity of tungsten carbide (figure 12, Pg 37) is a quantitative measure of the skeleton formed by the carbide grains, and is defined as the ratio of carbide grain boundary surface to total surface interface i.e. how many carbide grains touch each other?

Carbide Grain size

The size distributions of the tungsten carbide (figure 12) and cobalt phases in sintered alloys are determined mainly by the milling conditions and the initial size distribution of the carbide powder. The range of distribution can be altered by mixing powders of different particle sizes (21).

2.4.4 Effects of microstructural parameters on the hardness of tungsten carbide

Effect of cobalt content

As has been mentioned previously, the hardness decreases with increasing cobalt content in this range. The hardness also decreases linearly with increasing carbon content.

The addition of small amounts of tantalum carbide and/or titanium carbide has been found to increase the hardness without appreciably affecting the transverse rupture strength.

Effect of mean free path

The hardness of commercial alloys appears to be a simple function of the mean free path, the greater the mean free path, the softer the material, although it has been found that to describe the relationship precisely, an additional independent parameter is needed, such as particle size or composition.

Effect of grain size

The carbide grain size causes the hardness to decrease with increasing carbide grain size.

Although relatively few attempts have been made to find relationships between contiguity and mechanical properties, the studies that have been done have shown that the hardness increases with increasing contiguity.

2.4.5 Fracture Toughness

One of the major drawbacks in the use of WC-Co alloys is their brittleness. This brittleness is accompanied by low toughness and extreme sensitivity to microstructural defects. K_{IC}, the critical stress intensity factor, is a measure of the resistance to fracture.

An increase of the fracture toughness is a function of:

* An increase in the cobalt content
* An increase in the mean free path
* A decrease in hardness
* A decrease in contiguity.

2.5 EROSION OF TUNGSTEN CARBIDE COBALT ALLOYS

2.5.1 Introduction

Cemented WC-Co alloys, by virtue of their excellent wear resistance, are used extensively in the mining industry for drill tips; as machine tools or in any application where a high degree of wear is expected.

There are a number of factors that have been found to influence the relative wear resistance of WC-Co alloys, and these factors are discussed in the following sections.

2.5.2 Effect of material parameters

Hardness

Laugier (22) found the following relationship between erosion and hardness for a range of WC-Co composites using 200 to 500 alumina grit normally incident at about 140 m/s:

$$\text{Erosion} = 1.44 * 10^{11} * H^{-3.5}$$

He also found that current theories on indentation fracture to be inapplicable, possibly due to indentation size effects.

Larson-Basse (23) noted from the following graph that relatively soft cemented carbides follow the same general abrasion resistance-hardness relation as the more conventional metals and alloys, while the hard cemented carbides are located past a transition hardness level at which abrasion resistance increases dramatically.

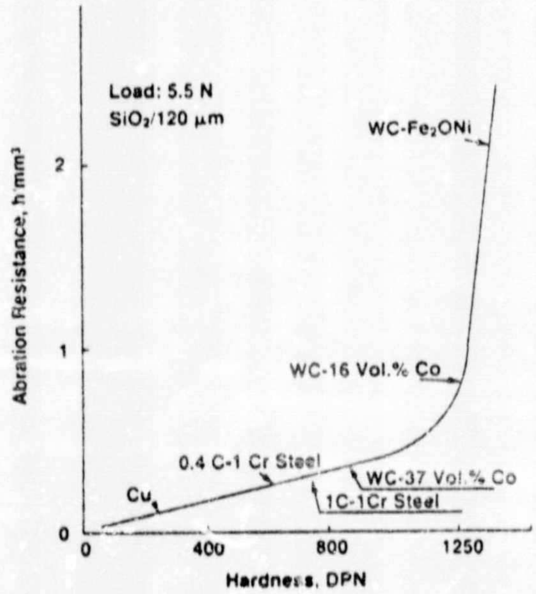

Figure 13. Effect of hardness on the abrasion of metals, alloys and cemented carbides by quartz abrasives. (After Larsen-Basse, 23).

This transition occurs at a point where the abrasives are no longer hard enough to indent the surface sufficiently to remove material in plastic deformation as microchips or by similar mechanisms. This means that the abrasive used in a test can have an enormous effect on the relative ranking of cemented carbides for abrasion resistance if the hardness of the abrasive falls in the same range as the alloys.

Figure 14, Pg 42, shows the relationship between hardness, composition and grain size. It shows that there is a direct relationship between the relative abrasion resistance and the hardness of the WC-Co alloy (24).

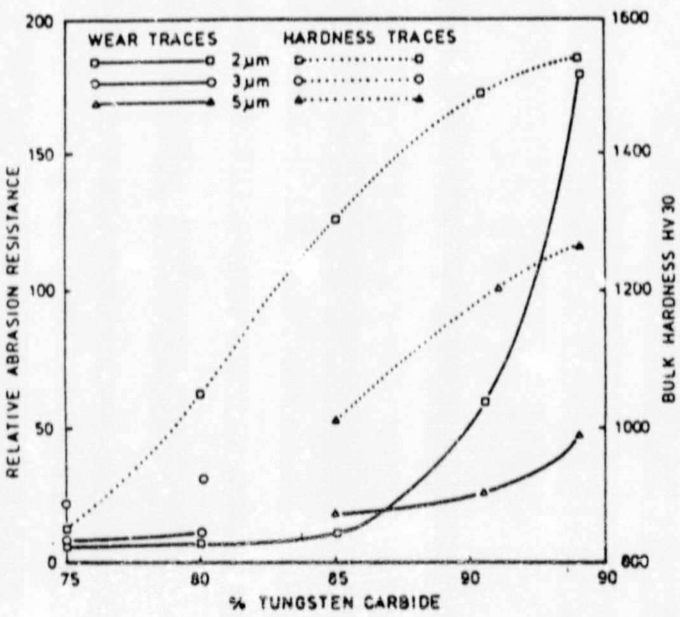

Figure 14. The relative abrasion resistance and hardness of WC-Co alloys as a function of composition and grain size. (After Ball, 24).

Fracture toughness

Chermant et al (25) have made a study of the relationship between the critical stress intensity factor K_{IC} and the abrasive wear resistance, using an abrading disc. When K_{IC} is plotted (figure 15, Pg 43) against the loss in weight of the specimen per minute, it is observed that the weight loss increases with K_{IC}. The material exhibiting most wear is that with the highest volume fraction of cobalt, and is thus in agreement with the fact that the harder the material, the smaller is K_{IC}, and the weight loss is consequently also smaller.

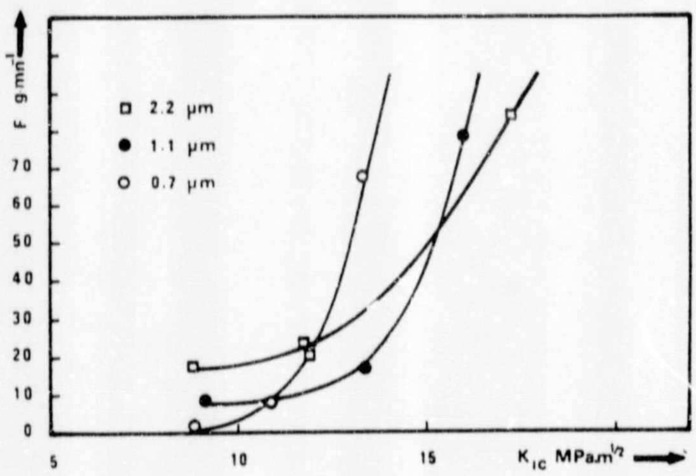

Figure 15. Variation of the loss in weight of the specimens of the abrading disk with K_{1c}. (After Chermant and Osterstock, 25)

Transverse rupture strength and compressive strength

Studies of the effect of the transverse rupture strength and compressive strength on the abrasion resistance of WC-Co alloys do not appear to have been reported in detail in the literature.

2.5.3 Effect of physical parameters

Cobalt content

The effect of increasing cobalt content is to decrease the wear resistance of the alloy (figure 16, Pg 44). Conrad et. al. (26) found that the erosion rate increased linearly with volume fraction of cobalt at all velocities, the slope increasing with velocity. They found that similar behaviour occurred for all impact angles considered.

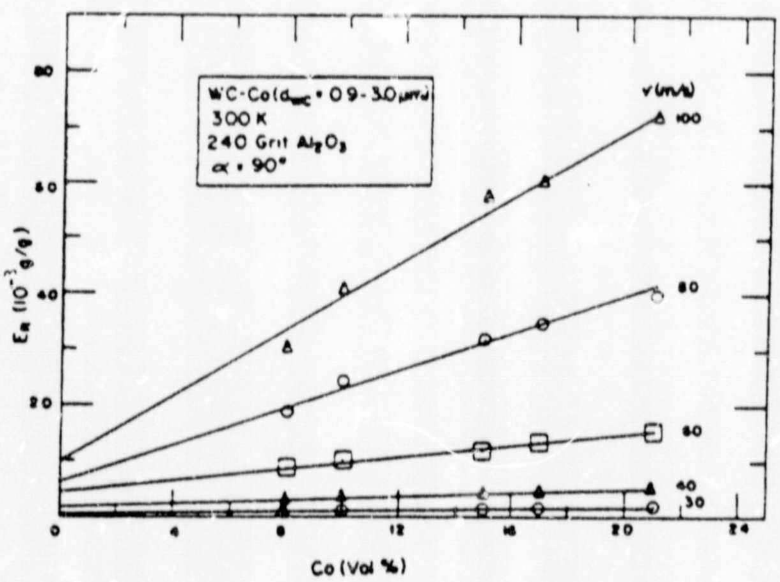

Figure 16. Effect of cobalt content on erosion rate as a function of particle velocity. (After Conrad et al, 26)

<u>Tungsten carbide grain size, mean free path and contiguity</u>
Ball (24) found that the wear resistance increases sharply for carbide contents greater than 90 percent and that the influence of grain size becomes significant at these higher carbide contents. These two facts indicate that either the contiguity or the intergranular separation (mean free path) of the tungsten carbide grains or both, have an important influence on the abrasion resistance of these alloys.

Conrad et. al. (27) using alloys of 6 to 10.5 % Co, grain sizes of .9 to 3 microns, mean free path of .3 to .9 microns and contiguity between .32 and .63, found that in general, at low velocities and/or small angles of impact, the erosion rate was only slightly dependent on the cobalt volume fraction, but increased with decrease in tungsten carbide grain size, decrease in the mean free path and increase in the tungsten carbide grain contiguity. Conversely, at higher velocities and/or large angles of impact, the erosion rate was more sensitive to the cobalt content and relatively independent of the contiguity, mean free path and grain size.

2.5.4 Effect of conveying parameters

Velocity

The greater the velocity, the greater the erosion. Conrad et. al. (27), using a cobalt content range of 6 to 10.5 wt %, found that the erosion resistance obeyed the commonly observed power law relationship of:

$$\text{EROSION} = \text{CONSTANT} * \text{VELOCITY}^n$$

where n is approximately 2 for impact angles less than 45°, and approximately 3 for impact angles = 15°. Figure 17, Pg 46, shows the effect of velocity as a function of impact angle.