The following table (Table 2) summarises the constants for the lines in figure 37, Pg 83, of the form:

\[
\text{LOG(EROSION)} = M \times \text{LOG(VELOCITY)} + C
\]

**MATERIAL DESCRIPTION**

<table>
<thead>
<tr>
<th>ALLOY</th>
<th>% Co</th>
<th>GRAIN SIZE</th>
<th>HARDNESS</th>
<th>M</th>
<th>C</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>FF6</td>
<td>6</td>
<td>0.56 ULTRAFINE</td>
<td>1837</td>
<td>3.79</td>
<td>-14.19</td>
<td>0.91</td>
</tr>
<tr>
<td>F6</td>
<td>6</td>
<td>1.85 FINE</td>
<td>1541</td>
<td>3.22</td>
<td>-10.25</td>
<td>0.91</td>
</tr>
<tr>
<td>M6</td>
<td>6</td>
<td>2.42 MEDIUM</td>
<td>1448</td>
<td>2.83</td>
<td>-8.94</td>
<td>0.89</td>
</tr>
<tr>
<td>C6</td>
<td>6</td>
<td>2.98 COARSE</td>
<td>1391</td>
<td>3.09</td>
<td>-9.67</td>
<td>0.88</td>
</tr>
<tr>
<td>C15</td>
<td>15</td>
<td>2.85 COARSE</td>
<td>1089</td>
<td>3.76</td>
<td>-10.98</td>
<td>0.92</td>
</tr>
<tr>
<td>C30</td>
<td>30</td>
<td>2.17 COARSE</td>
<td>780</td>
<td>3.97</td>
<td>-10.92</td>
<td>0.92</td>
</tr>
<tr>
<td>MS</td>
<td></td>
<td>MILD STEEL</td>
<td>200</td>
<td>3.55</td>
<td>-8.95</td>
<td>0.87</td>
</tr>
</tbody>
</table>

Table 2. Table of coefficients for each material, including R² which is an indication of accuracy.

Mills and Mason (2), from their work on mild steel bends have proposed a velocity exponent of 4.5, taking into account the penetration depth i.e.

\[
\text{PIPE BEND EROSION} = \text{CONSTANT} \times \text{AIR VELOCITY}^{4.5}
\]

From the work reported here, it has been found that the velocity exponent for mild steel is of the order of 3.5, although Mills et al used radiused bends.
Figure 37. Log-log plot of erosion versus air velocity.
Solids mass flowrate = 48 kg/min.
Impact angle = 70°.
7.1.2 Influence of solids mass flow ratio

Figure 38, Pg 85, shows the results of the constant velocity, varying solids mass flow ratio tests. There appears to be a definite trend i.e. with all materials tested, the erosion rate decreases with an increase in solids mass flow ratio. In fact, from these results, it may be argued that there is a threshold solids mass flow ratio above which the erosion rate becomes negligible. In this case the threshold value is at approximately 2.1, (corresponding to a solids mass flow rate of approximately 60 kg/min), although further work is necessary to verify this conclusively.

It is suggested that the effect of an increase in the solids mass flow rate, or more specifically phase density, is to increase the interference and shielding effect between particles as well as between the particle/surface interface.

Figure 38, Pg 85, confirms the trend of the erosion resistance already displayed by figure 37, Pg 83, of the specimens tested i.e. the ultrafine 6% cobalt alloy performed the best, followed by the 6% cobalt, varying grain size range, the coarse grained, 15% cobalt, 30% cobalt and finally mild steel.

It is worth noting that at the high mass flow ratios (above approximately 65kg/min or a mass flow ratio of 2.3), there is very little difference in the erosion resistance of the expensive low cobalt, ultrafine grained tungsten carbide alloy and mild steel.
Figure 38. Results of the erosion versus phase density or mass flow ratio tests.
Velocity = 39 m/s.
Impact angle = 70°.
### 7.1.3 Influence of impact angle

Figure 39, Pg 88, shows the results of the impact angle tests. Here it can be seen that the tungsten carbide alloys are all relatively insensitive to a change in impact angle over this range, although the same relative erosion resistance ranking as in the previous two sections is present. Tests could not be conducted at 90° as the particles tended to pack up against the specimen holder.

The theory that ductile materials show a maximum erosion rate well below 90° holds for the curve presented for mild steel, where the maximum is approximately 40°. It can be seen that maximum erosion of the tungsten carbide alloys does not occur at the higher impact angles which is what one would expect of a brittle material: the results presented here imply a ductile type response. This is in direct contrast to the results of Conrad et al (27), (see figure 17, Pg 46), who found that maximum erosion occurred at 90°. This can be explained by the fact that the cobalt has a toughening effect on the alloy. If one considers the performance of C30, which has 30% by weight or close to 50% by volume cobalt content, it can be said that C30 behaves in a ductile manner. Examination of the curve for C30 shows a ductile type response to impact angle, where a shallow maximum is present at approximately 45°.
The fact that all the WC alloys display a maximum below 90° can be explained by the effect of the erodant size, acting synergistically with the effect of plastic deformation. At high impact angles, more energy goes into the fracture of the erodant than at lower impact angles. (The large particle size of the erodant, 4mm down to sub micron powder, implies that the critical shear stress of the erodant is low, due to the volumetric effect.) Thus less energy goes into fracture of the WC surface at higher impact angles (for a constant energy input) and therefore less erosion occurs. The angle of maximum erosion is therefore a function of the critical fracture stress of the erodant particles, and appears to be approximately 45°. This explanation is in agreement with the results obtained by Anand et al (28), who found that the angle of maximum erosion decreased below 90° as the erodant size increased, (see figure 19, Pg 48).

A more detailed explanation of the point of maximum erosion is given in section 7.5, Pg 109, Effect of plastic deformation.
Figure 39. Graph of erosion versus impact angle.

Velocity = 39m/s.

Solids mass flow rate = 68kg/min.

<table>
<thead>
<tr>
<th>ALLOY</th>
<th>% Co</th>
<th>GRAIN SIZE</th>
</tr>
</thead>
<tbody>
<tr>
<td>FF6</td>
<td>6</td>
<td>0.56 ULTRAFINE</td>
</tr>
<tr>
<td>F6</td>
<td>6</td>
<td>1.85 FINE</td>
</tr>
<tr>
<td>M6</td>
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</tr>
<tr>
<td>C6</td>
<td>6</td>
<td>2.98 COARSE</td>
</tr>
<tr>
<td>C15</td>
<td>15</td>
<td>2.85 COARSE</td>
</tr>
<tr>
<td>C30</td>
<td>30</td>
<td>2.17 COARSE</td>
</tr>
<tr>
<td>MS</td>
<td></td>
<td>MILD STEEL</td>
</tr>
</tbody>
</table>
7.2 Influence of tungsten carbide parameters

7.2.1 Influence of cobalt content

From figure 40, Pg 90, it can be seen that the overall effect of the influence of cobalt content is to decrease the erosion resistance of the alloy. Moreover, the graph shows that at low conveying air velocities there is very little difference in the erosion resistance of the various grades of alloys, hence one might select the toughest alloy for a particular application and still retain the erosion resistance of the low cobalt alloys, provided the application is at low conveying velocities. At higher conveying velocities, the effect of higher cobalt content is to decrease the erosion resistance.

It appears from these results and those of other researchers (20, 25, 27), that it is the cobalt content which primarily controls the wear performance of the tungsten carbide alloys. This is illustrated by the trend which shows that the wear resistance decreases with increasing cobalt content. This can be explained by virtue of the fact that with a high cobalt content there is more softer material in the alloy and the intercarbide spacing (mean free path) is greater. The mechanism of erosion in this case was preferential removal of the soft binder material i.e. cobalt. The removal of cobalt has two consequences; the grains are no longer supported and thus fall off, and the grains are no longer under compression, thus they fracture more easily. It is thus understandable that the high cobalt content alloys display less erosion resistance than the low cobalt alloys.
Figure 40. Graph of erosion versus cobalt content, showing the influence of velocity.
Impact angle = 70°.
Solids mass flow rate = 48 kg/min.
WC grain size = coarse.
The following figures illustrate the effect of cobalt content on erosion as the mass flowrate and impact angle are varied.

Figure 41, Pg 92, shows that at low mass flow rates the erosion rate is high, and decreases for increasing mass flowrates. It can be argued that above a certain threshold mass flowrate the effect on erosion becomes insignificant, as can be seen by the curves for 68 kg/min and 83 kg/min.

Figure 42, Pg 93, shows that there is maximum erosion around 50°, and minimal erosion for the higher impact angles.
Figure 41. Erosion versus cobalt content as a function of mass flowrate.

Velocity = 39 m/s.
Impact angle = $70^\circ$.
WC grain size = coarse.
Figure 42. Erosion versus cobalt content as a function of impact angle.
Velocity = 39 m/s.
Solids mass flowrate = 68 kg/min.
WC grain size = coarse.
7.2.2 Influence of tungsten carbide grain size

Figure 43, Pg 95, illustrates the effect of the tungsten carbide grain size for the 6% cobalt range of alloys. An increase in velocity causes an increase in erosion. Noting the scale of the erosion (ordinate axis) compared to all the previous graphs, it can be seen that over the range of pneumatic conveying parameters tested, there is very little difference of practical significance in erosion resistance between the alloys presented here, excepting the ultrafine grained alloy, which displays a high erosion resistance. However, the error bands between the fine, medium and coarse grained alloys are not consistent, the medium grained alloy displaying a higher erosion resistance than the fine grained alloy. This anomaly is discussed in greater detail in section 7.5, Pg 109, Effect of plastic deformation. This indicates an optimum erosion resistant alloy apart from the ultrafine grained alloy, which is very expensive to produce.
Air velocity = 28 m/s
Air velocity = 39 m/s
Air velocity = 52 m/s

Figure 43. Graph of erosion versus tungsten carbide grain size showing the influence of velocity. Impact angle = 70°. Solids mass flowrate = 48 kg/min. Cobalt content = 6% (wt%).
The following figures illustrate the effect of grain size on erosion as the mass flowrate and impact angle are varied. Figure 44, Pg 97, shows that at low mass flowrates the erosion rate is high, and decreases for increasing mass flowrates. It can be seen that for small grain sizes the effect of mass flowrate over the whole range becomes insignificant, not only at the higher mass flowrates. Figure 45, Pg 98, shows that there is maximum erosion around 50°, and minimal erosion for the higher impact angles. (See section 7.5, Pg 109, Effect of plastic deformation).
Figure 44. Erosion versus grain size as a function of mass flowrate.

Velocity = 39 m/s.
Impact angle = 70°.
Cobalt content = 6% (wt%).
Figure 45. Erosion versus grain size as a function of impact angle.
Velocity = 39 m/s.
Solids mass flowrate = 68 kg/min.
Cobalt content = 6%.
7.2.3 Influence of Hardness

Figure 46, Pg 100, shows that there is a marked effect of bulk hardness at the higher conveying velocities. It can be seen that above approximately 1200 Vickers hardness the erosion decreases substantially. Therefore, if an application only requires hardness for erosion resistance, it would be pertinent to choose an alloy around 1200 Vickers or just above, to take advantage of the greater toughness. (This confirms the importance of the hardness of the erodant, in this case approximately 1200 Vickers, relative to the material hardness when attempting to reduce wear).

Again it can be seen that at low conveying velocities, there is very little difference in the erosion resistance over the whole range of hardnesses presented here.
Figure 46. Graph of erosion versus tungsten carbide hardness showing the effect of velocity. Impact angle = 70°. Solids mass flowrate = 48 kg/min.
The following figures illustrate the effect of hardness as a function of mass flowrate and impact angle. Figure 47, Pg 102, shows that at low mass flow rates the erosion rate is high, although above 1400 Vickers the effect of mass flow rate becomes insignificant. At the higher mass flowrates the effect of hardness is minimal. Figure 48, Pg 103, shows that there is maximum erosion around 50°, and minimal erosion for the higher impact angles.
**Author** Freinkel D M (David M)

**Name of thesis** Experimental Investigation Into The Wear Resistance Of Tungsten Carbide-cobalt Liners In A Full Scale Pneumatic Conveying Rig.  1988

**PUBLISHER:**
University of the Witwatersrand, Johannesburg
©2013

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