GLOBAL TRENDS IN ORE HARDNESS

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ABSTRACT

The SMC Test® has become one of the most popular laboratory tests for determining the ore hardness from an AG/SAG, HPGR and Crusher perspective. To date over 35,000 tests have been conducted. These tests cover over 1,300 different ore bodies. Significantly these deposits are distributed globally across every continent, including over 82 different countries and over 30 different commodities. This paper describes this huge data base and looks at trends associated with geographical location and mineral species.

KEYWORDS

Geometallurgy, hardness testing

INTRODUCTION

As the main subject of this paper concerns global trends in comminution circuit feed ore hardness using SMC Test$^{®}$ parameters, it is first appropriate to establish that these parameters are relevant in the first instance as accurate indicators of hardness.

The SMC Test$^{®}$ was developed by Steve Morrell and was commercialised via the company, SMC Testing Pty Ltd, in 2004. The "SMC" acronym stands for **S**teve **M**orrell **C**omminution (not SAG Mill Comminution as appears in some literature). Since its inception in 2004 it has become the most popular and versatile laboratory ore hardness test in the world, with over 35,000 tests having been completed to date, covering over 1300 different ore bodies. It is routinely used in design, optimisation and ore body profiling projects. The test is unique in that from relatively small amounts of drill core it provides work indices that are used in power-based equations for predicting the specific energy of AG/SAG mill circuits (DWi parameter), conventional crushing circuits (Mic parameter), HPGR circuits (Mih parameter) and in combination with the Bond ball mill work index test, the total comminution circuit (Mia, Mib parameters) and ball mill circuit (Mib parameter) as well as providing parameters for simulation modelling of AG/SAG and crushing circuits (A,b and ta) (Morrell 2004, 2008, 2009, 2010). Its popularity has been driven by the fact that the test and its associated equations have been validated through benchmarking using 186 data sets from 117 different circuits which cover the full range of ore types, circuit types and equipment sizes, as seen in Tables 1 and 2. The high degree of predictive accuracy that is provided is illustrated in Figures 1-5 which show the observed and predicted specific energies of the total comminution circuit, AG/SAG mill, ball mill, crushing and HPGR circuits respectively from these benchmarking exercises. This success has led many leading engineering companies, equipment suppliers and mining companies to use the SMC Test$^{®}$ as a standard for design, optimisation and geometallurgical modelling of comminution circuits (Alruiza et al., 2009; Buckingham et al., 2011; Festa et al, 2015; Lane et al 2013; Wang et al., 2015; Wirfiyata & McCaffery, 2011).

Table 1 – Circuits Covered by Benchmarking Data

Circuits	Data sets
Primary crushing	7
Secondary/tertiary crushing	17
Pebble crushing	7
Open/closed circuit HPGR	37
Rod/ball mill	2
Crush/ball mill	5
Crush/HPGR/ball mill	2
Single stage AG	8
Single stage SAG 1° crush	15
Single stage SAG 2° crush	2
AB	5
ABC-A	7
ABC-B	2
SAB 1° crush	30
SAB 2° crush	3
SABC-A 1° crush	30
SABC-A 2° crush	3
SABC-B	4
Total benchmarking data sets	186

Table 2 – Parameter Ranges Covered by Benchmarking Data

Parameter	Units	max	min
Ore characteristics			
DWi	kWh/m^3	14.2	1.7
Bond ball Wi	kWh/tonne	26	6
JK A*b		182	20
sg		4.63	2.45
AG/SAG mill circuits			
F80	mm	212	19.4
T80	microns	7770	140
P80 (single stage mills only)	microns	415	60
Diameter inside shell	ft	40	6
Length (EGL)	ft	31	2
Ball load	%	25	0
Speed	% crit	90	58
Length/Diameter ratio		2.0	0.3
Ball mill circuits			
P80	microns	257	45
Diameter inside shell	ft	26	10
Length (EGL)	ft	40.5	13
Ball load	%	45	20
Speed	% crit	82	67
Length/Diameter ratio		2.0	1.0

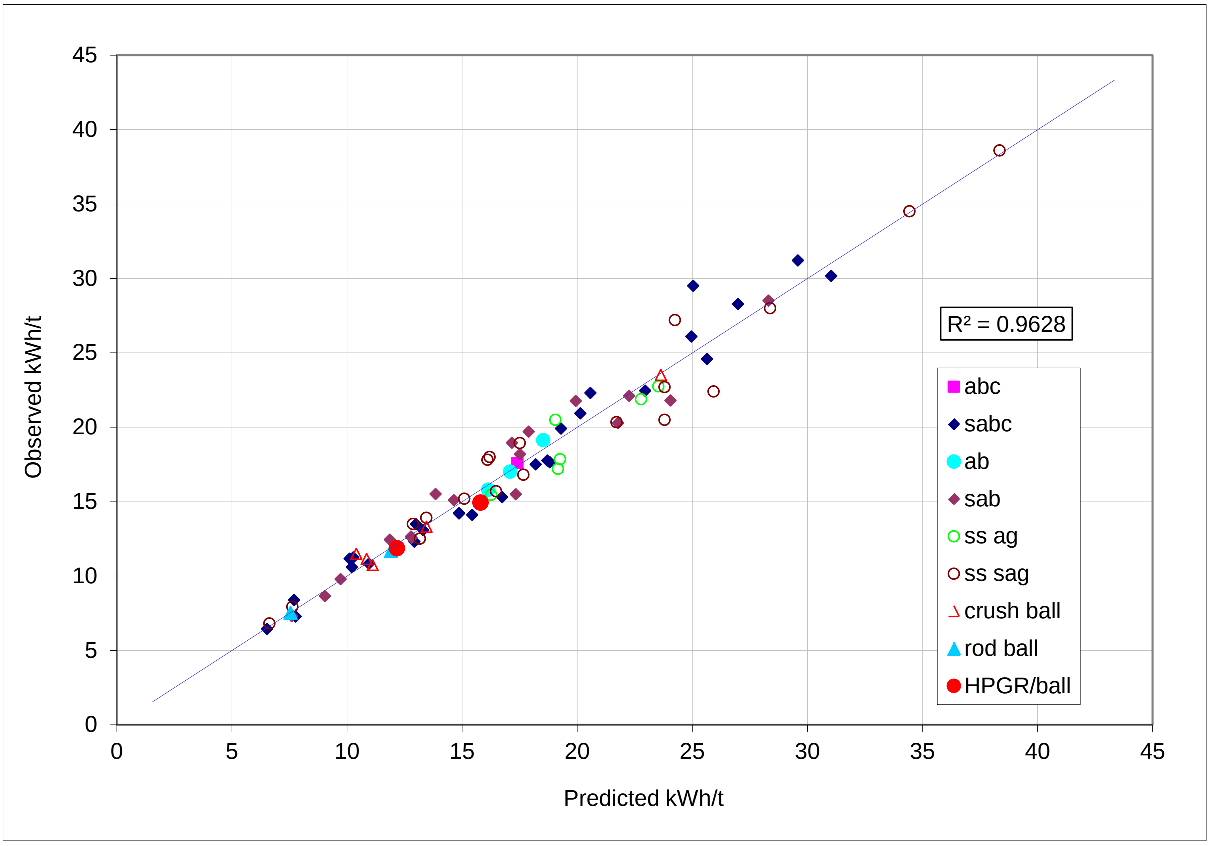

Figure 1 – Benchmarking Data – Observed vs Predicted Total Comminution Circuit Specific Energy Using the SMC Test®

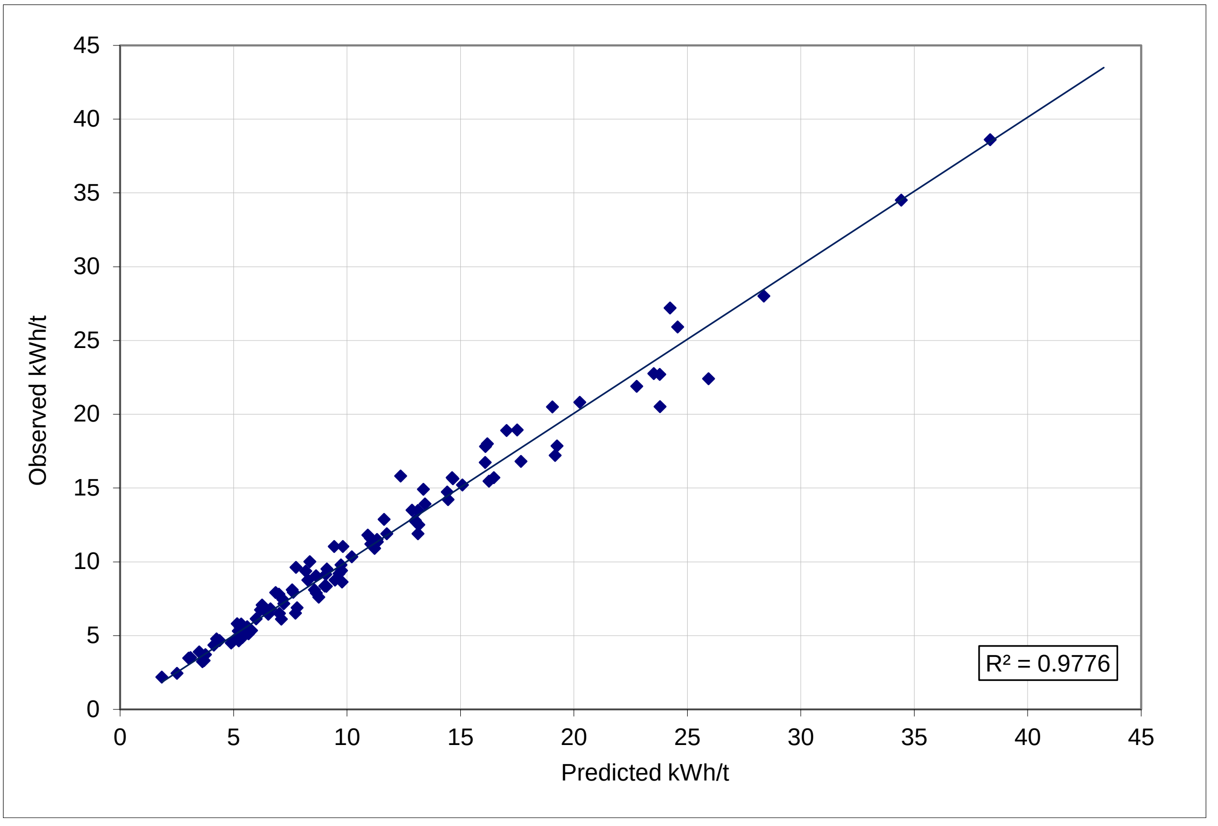

Figure 2 – Benchmarking Data – Observed vs Predicted AG/SAG Circuit Specific Energy Using the SMC Test®

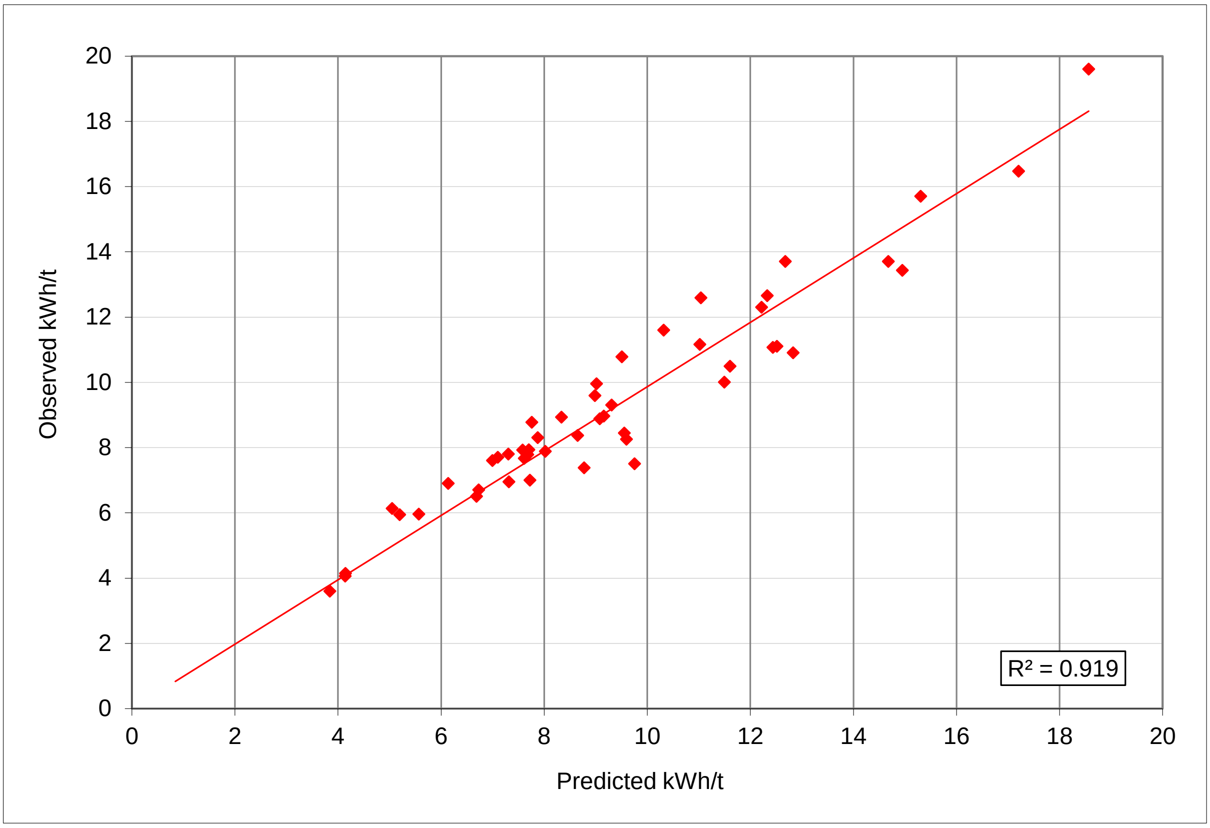

Figure 3 – Benchmarking Data – Observed vs Predicted Ball Mill Circuit Specific Energy

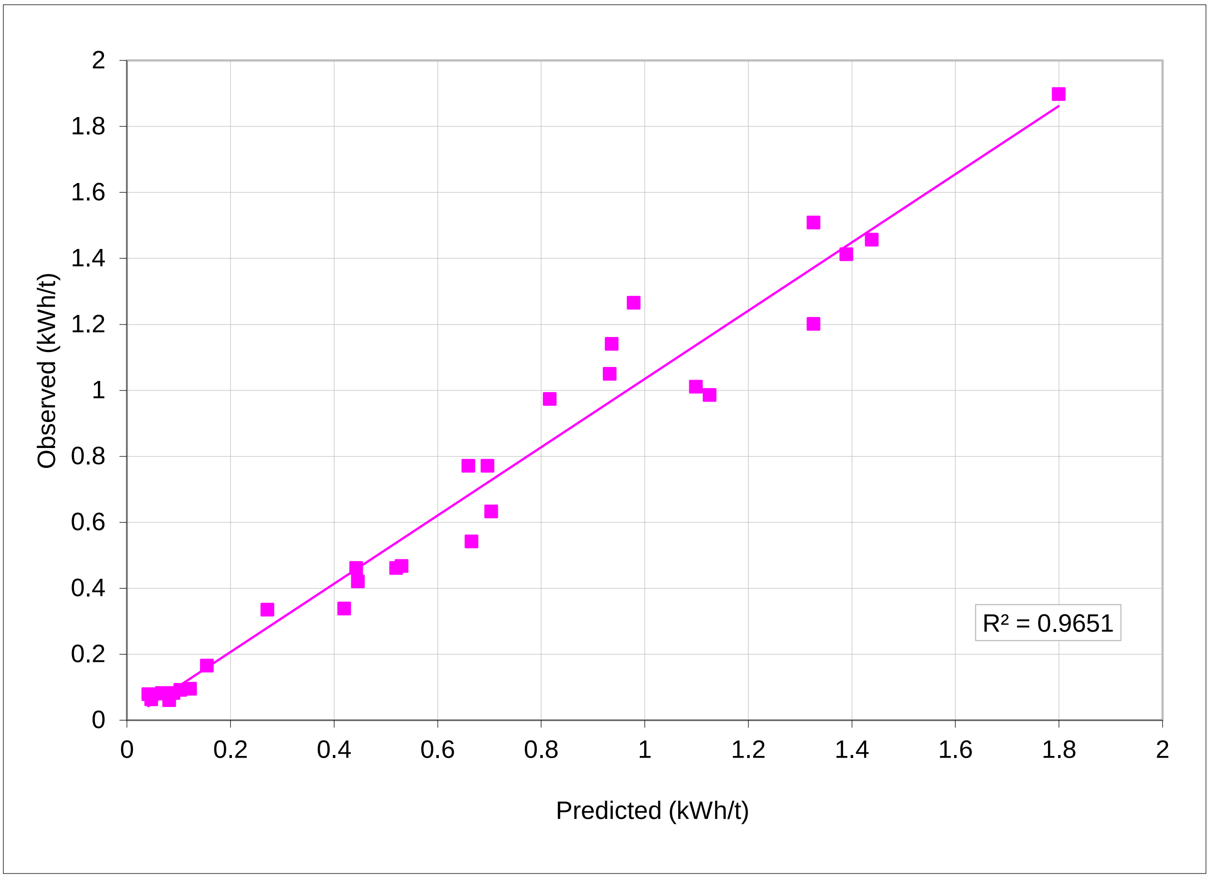

Figure 4 – Benchmarking Data – Observed vs Predicted Crushing Circuit Specific Energy Using the SMC Test®

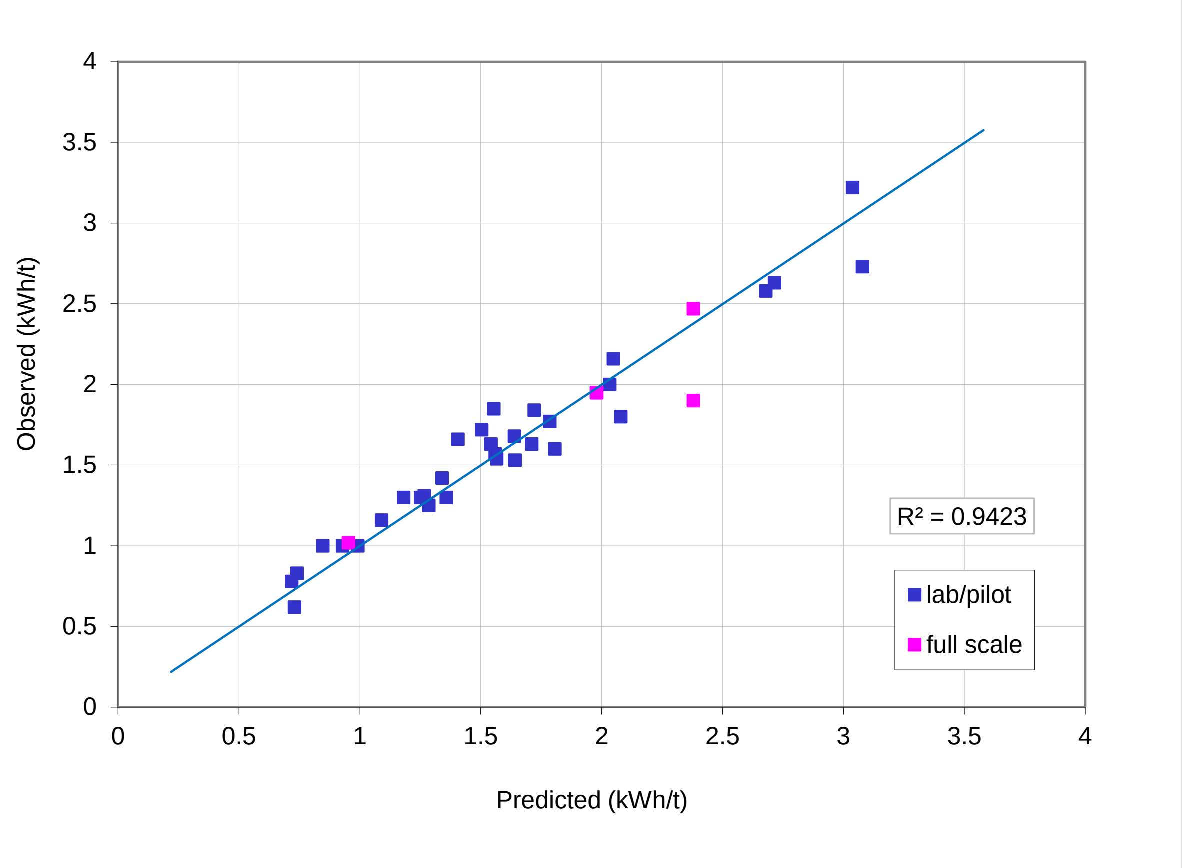

Figure 5 – Benchmarking Data – Observed vs Predicted Total HPGR Circuit Specific Energy Using the SMC Test®

DATA BASE ANALYSIS

Countries and Commodities

Having established the accuracy of the SMC Test® parameters from a comminution perspective, observed differences in these parameters across geographical boundaries and between commodities can now be reviewed in the light of their statistically significant relevance. To date over 35000 SMC Tests have been conducted. Samples have come from 82 different countries, a list of which is given in Appendix 1. Commodities covered are listed in Appendix 2 and number a total of 30. It should be noted that in classifying each test the primary commodity has been recorded, though in many cases ores contain a number of commodities eg Copper/Gold, Lead/Zinc etc. If the data are grouped geographically then the distribution between continents is as shown in Figure 6. South and Central America dominate the distribution, accounting for almost 43% of total tests, with North America and Oceania accounting for 23% and 17% respectively. The commodity distribution is shown in Figure 7 and indicates that copper ore tests alone account for 58% with gold accounting for 22%. Considering the trends in both these figures, it is perhaps not surprising that South and Central America account for such a large percentage of tests given the importance of this continent in terms of copper production. This is illustrated in Figure 8, which compares relative copper production by continent with the relative number of SMC Tests. As can be seen a close correspondence is seen and to a large extent reflects the supposition that the number of ore characterisation tests should be proportional to the size of ore deposits.

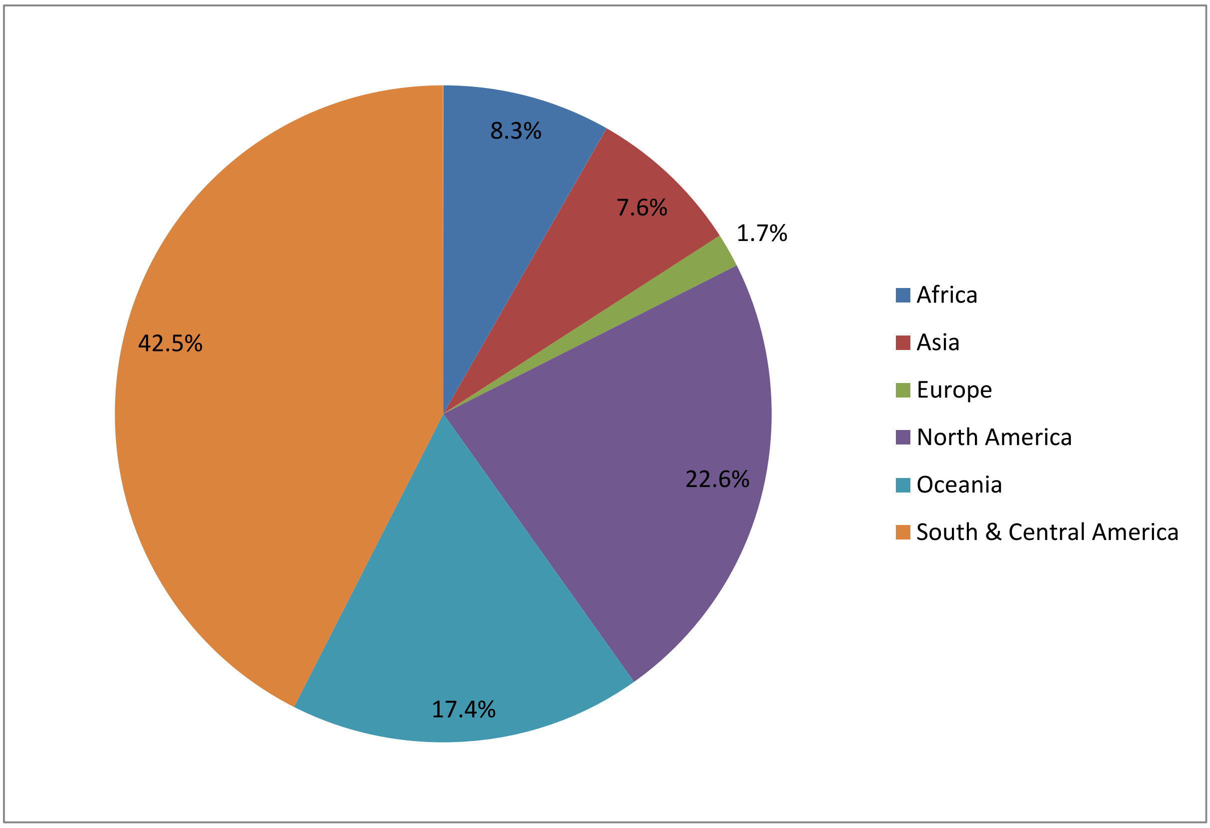

Figure 6 – Distribution of SMC Tests by Continent

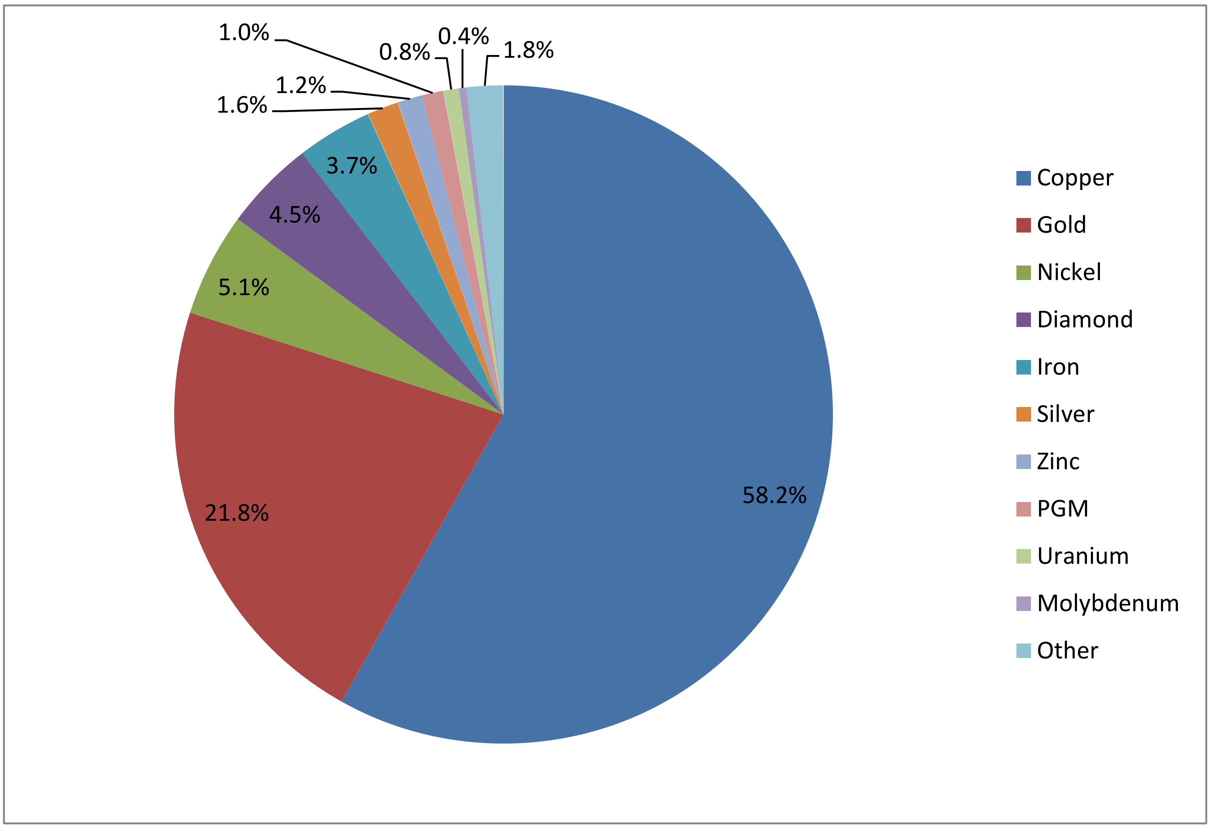

Figure 7 – Distribution of SMC Tests by Commodity

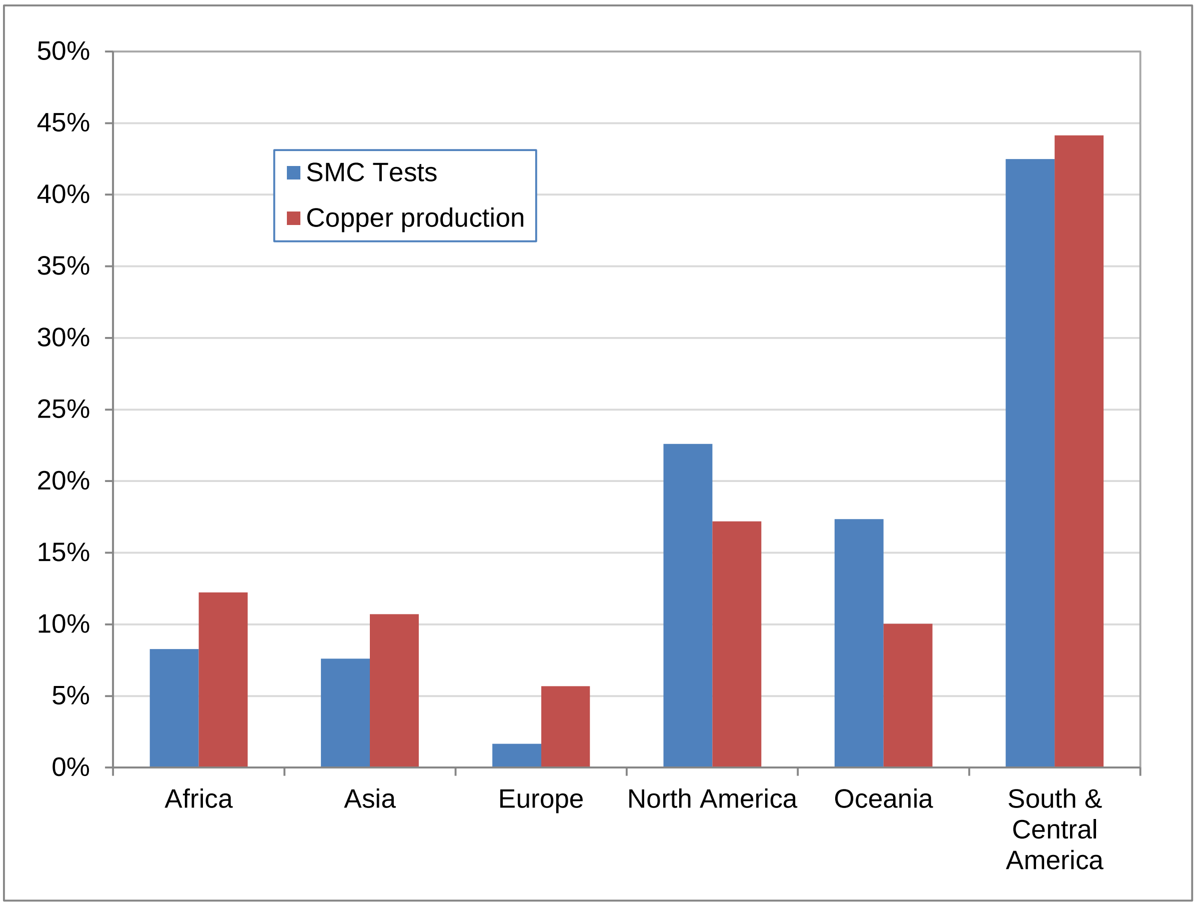

Figure 8 – Copper Production vs SMC Test Distribution by Continent

HARDNESS ANALYSIS

Overall

Given that the main subject of the conference is AG/SAG milling the hardness analyses mainly concentrate on statistics associated with the DWi parameter as it is this parameter that is used to predict AG/SAG circuit performance. Figure 8 shows the cumulative distribution of the DWi, using the 35000+ tests carried out to date. The minimum value is 0.15 kWh/m^3 and the maximum value is 22 kWh/m^3. The 50th percentile value is 6.6 kWh/m^3. The JK A*b parameter is also provided by the SMC Test® and although is not used directly in power-based equations to predict AG/SAG performance it is used in simulations and does provide a qualitative indication of ore hardness. Remembering that high values of A*b indicate a soft ore, the cumulative distribution is shown in Figure 9. The minimum value is 9.4, the maximum value is 1320 and the 50th percentile is 43. Note that in Figure 9 the x-axis has been represented in logarithmic space. This is because the variation in hardness with A*b is distinctly non-linear. As a result plotting the values in logarithmic space helps view the distribution more clearly.

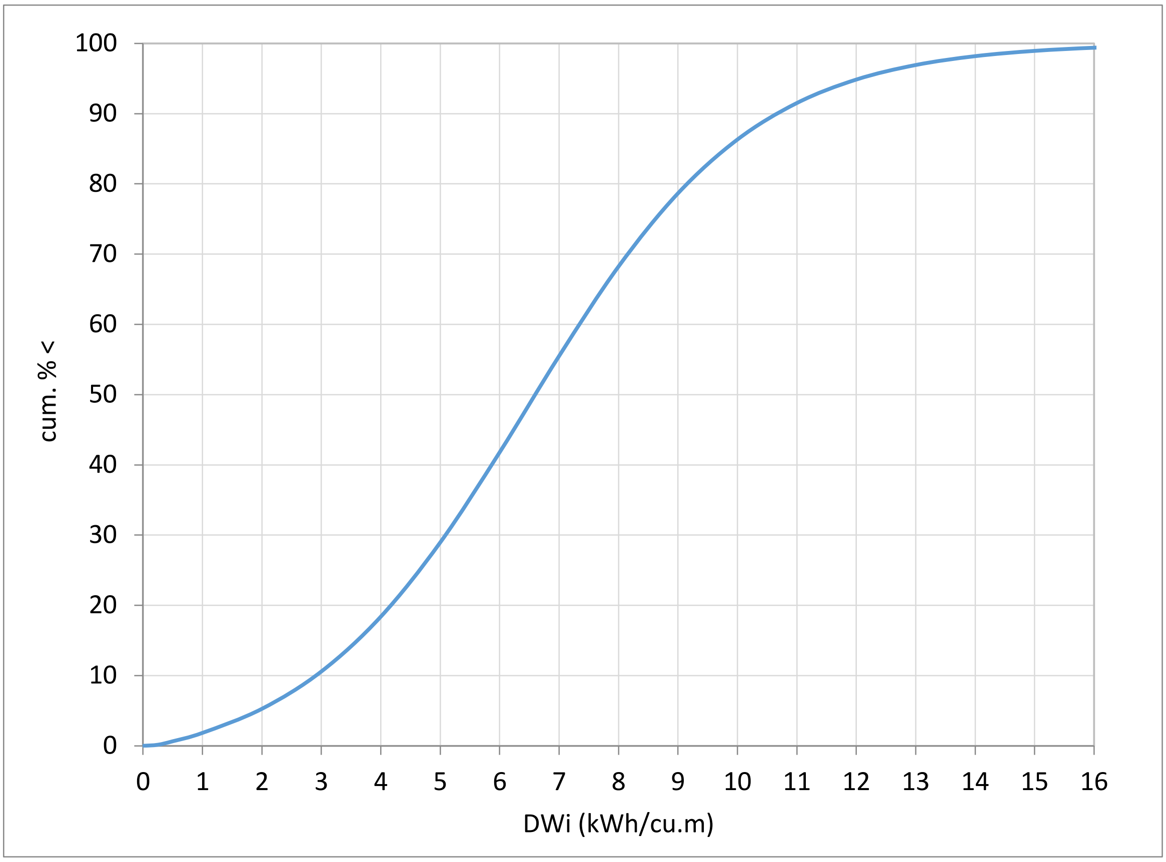

Figure 8 – Cumulative Distribution of DWi Values

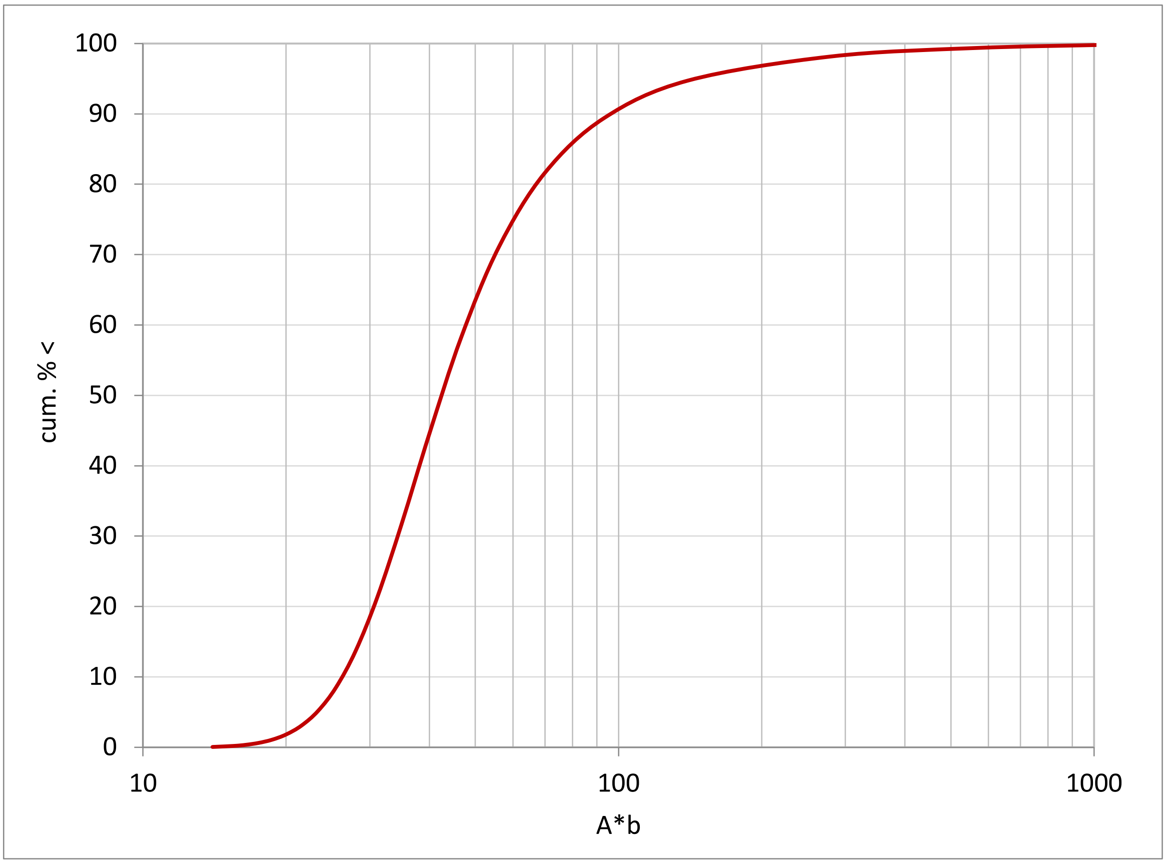

Figure 9 – Cumulative Distribution of A*b Values

Commodities

The mean DWi values by commodity are given in histogram form in Figure 10. Only commodities that account individually for more than 0.1% of total numbers of SMC Tests have been included. As can be seen there is a very large variation between commodities, with Tungsten ore topping the list with a mean DWi of almost 10 kWh/m^3 and bauxite being the softest with a mean value of almost 2 kWh/m^3. Of note is the interesting difference between Hematitic and Magnetitic iron ores, which indicate that, on average, the former is much softer than the latter and that the sg of Hematite ores is higher (3.75) than that of Magnetite ores (3.4). This is probably due to the fact that Hematite ores tend to have a higher iron grade than Magnetite ores and hence tend to be denser.

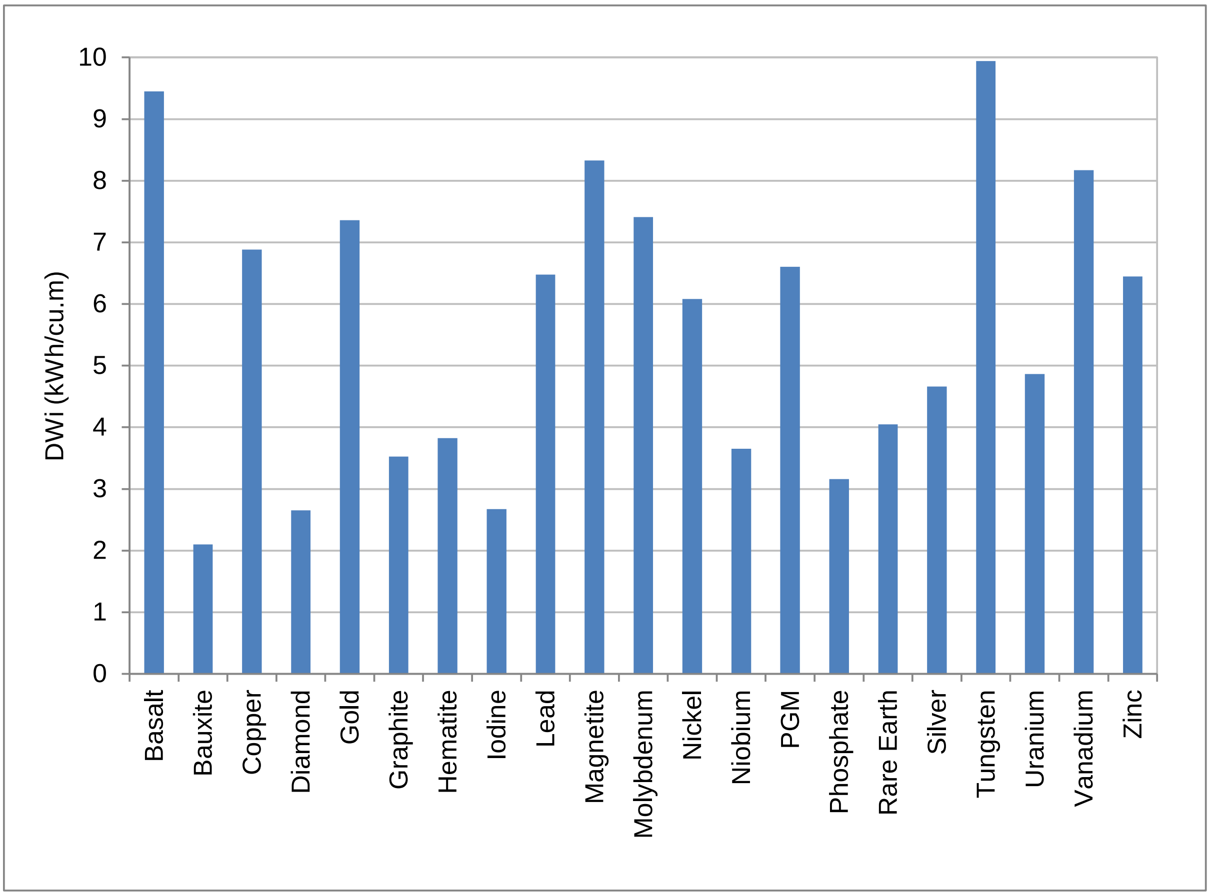

Figure 10 – Mean DWi Value by Commodity

Geographical

The mean DWi by continent is shown in Figure 11 and shows that on average the ores tested from Asia and North America are relatively soft, whereas those from Europe and Oceania are relatively hard. Interestingly a similar pattern is seen when the sg of the ores are also calculated on a continent-by-continent basis (Figure 12). Change in ore sg is often overlooked by Minerals Processors as an excellent indicator in many cases of changes in ore types. Hence the differences in Figure 11 are a reflection of the different make up of ores in each continent. Figure 12 illustrates this very well by comparing the distribution of tests by commodity between Africa and Oceania

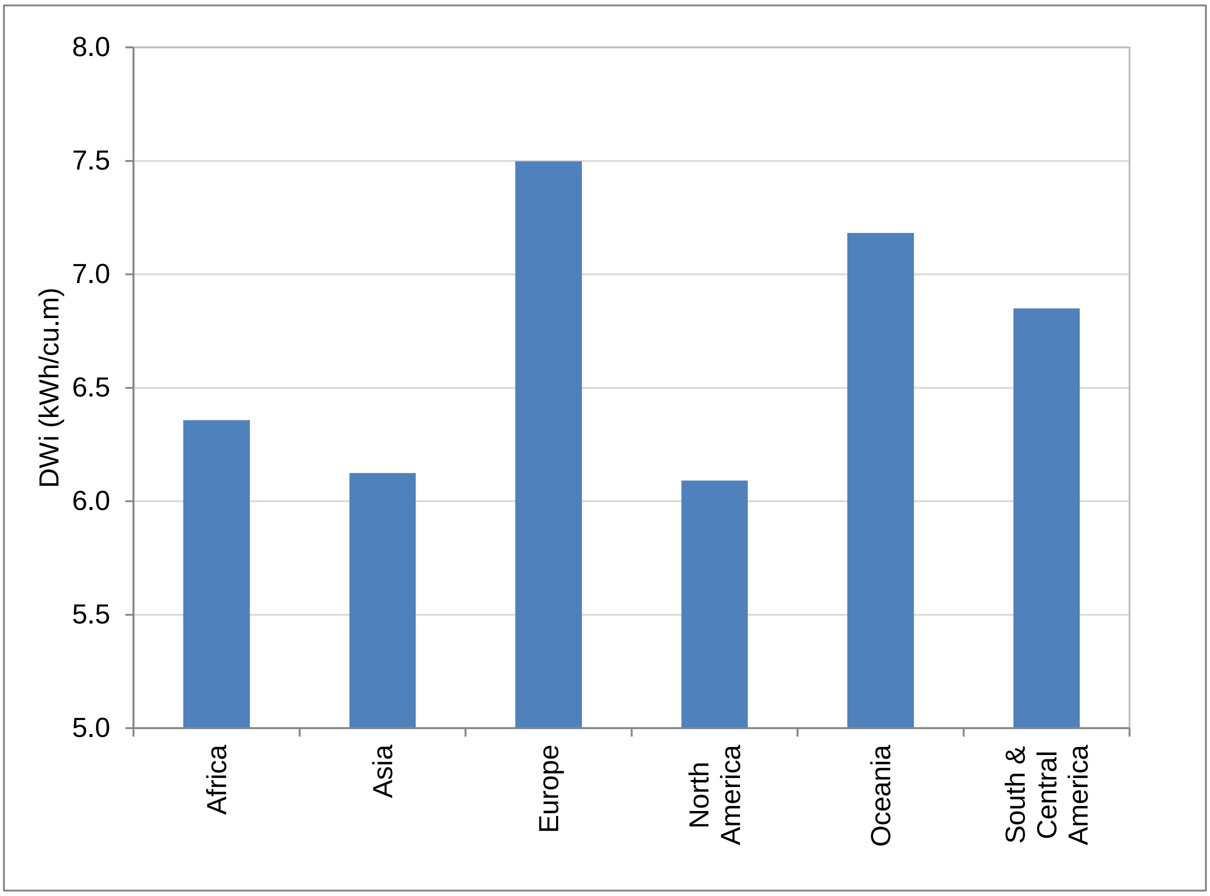

Figure 11 – Mean DWi by Continent

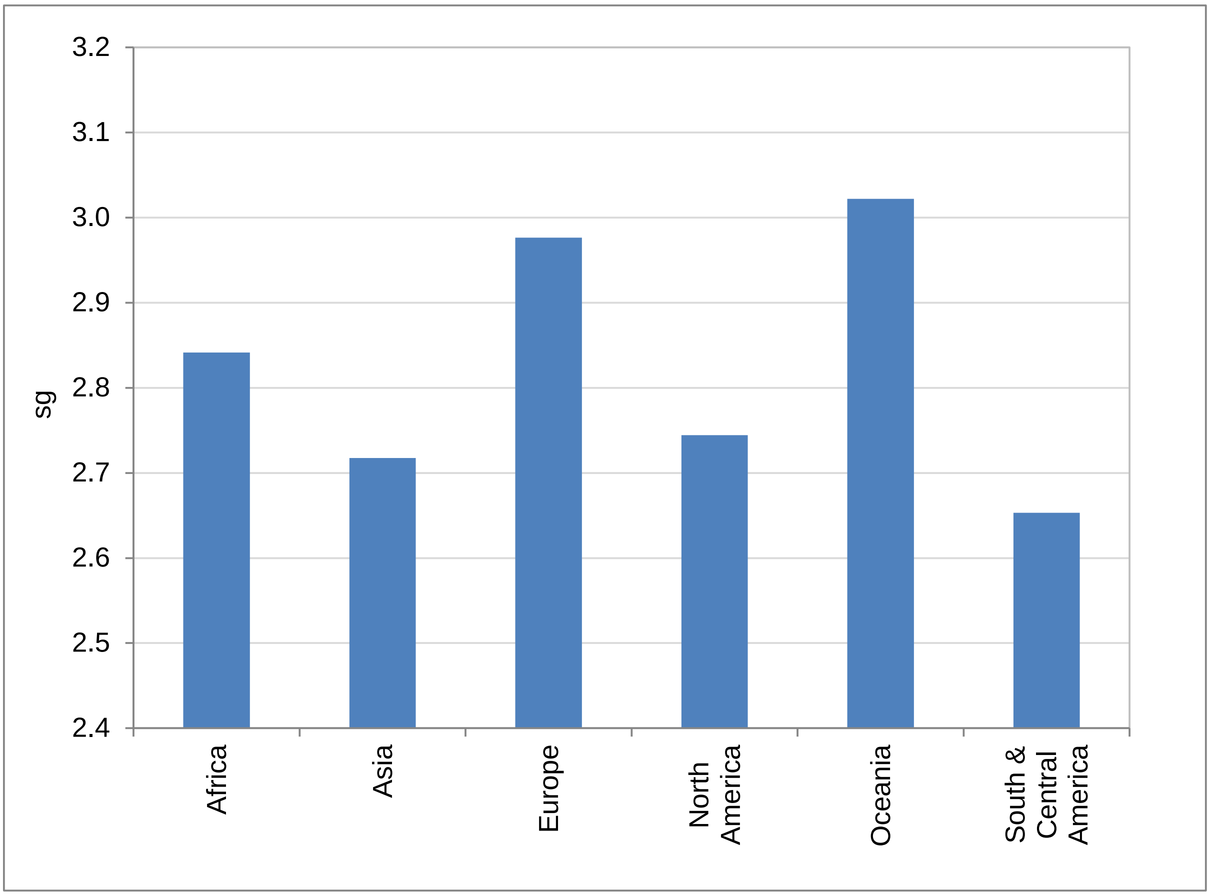

Figure 12 - Mean SG by Continent

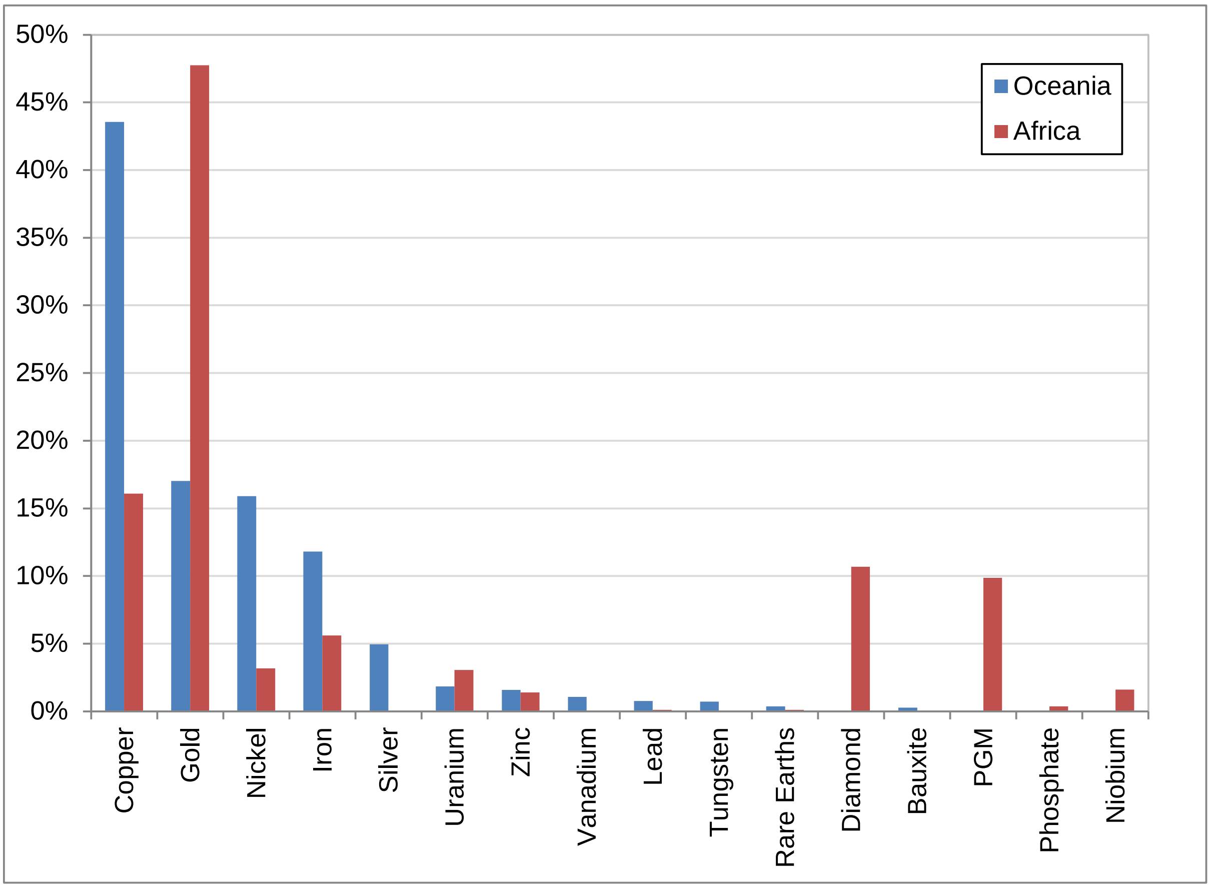

Figure 13 - Distribution of SMC Tests by Commodity for Africa and Oceania

As copper and gold between them account for 80% of all tests, it is interesting to look at how the mean hardness of these deposits vary by continent. Figure 14 shows the histogram for copper, where it can be seen that there are significant differences in hardness between some of the continents, particularly Africa and Europe. Asia, North America and South/Central American values are all relatively similar, with Oceania being marginally higher. Figure 15 shows the equivalent gold deposit histogram. A very different distribution is seen, with the highest hardness values coming from North American deposits, followed closely by Africa and Oceania.

Interestingly, there have been some claims that South American Porphyry Copper deposits are somehow different to those elsewhere and that the SMC Test® when used to predict specific energy tends to giver higher values than observed for such deposits. Figure 14 indicates that there is nothing significantly different about the hardness of South/Central American copper deposits and that they have a similar hardness to the overall average of all copper deposits. Figure 16 shows the predicted vs observed circuit specific energies for South American Porphyry deposits as well as all other copper deposits, the results having been separated out from the benchmarking data in Figure 1. There appears to be no obvious bias in the results, all data being equally well predicted. The conclusion from this analysis is that there is nothing “special” about the hardness of South American porphyries and that specific energies are predicted accurately from the use of the SMC Test®.

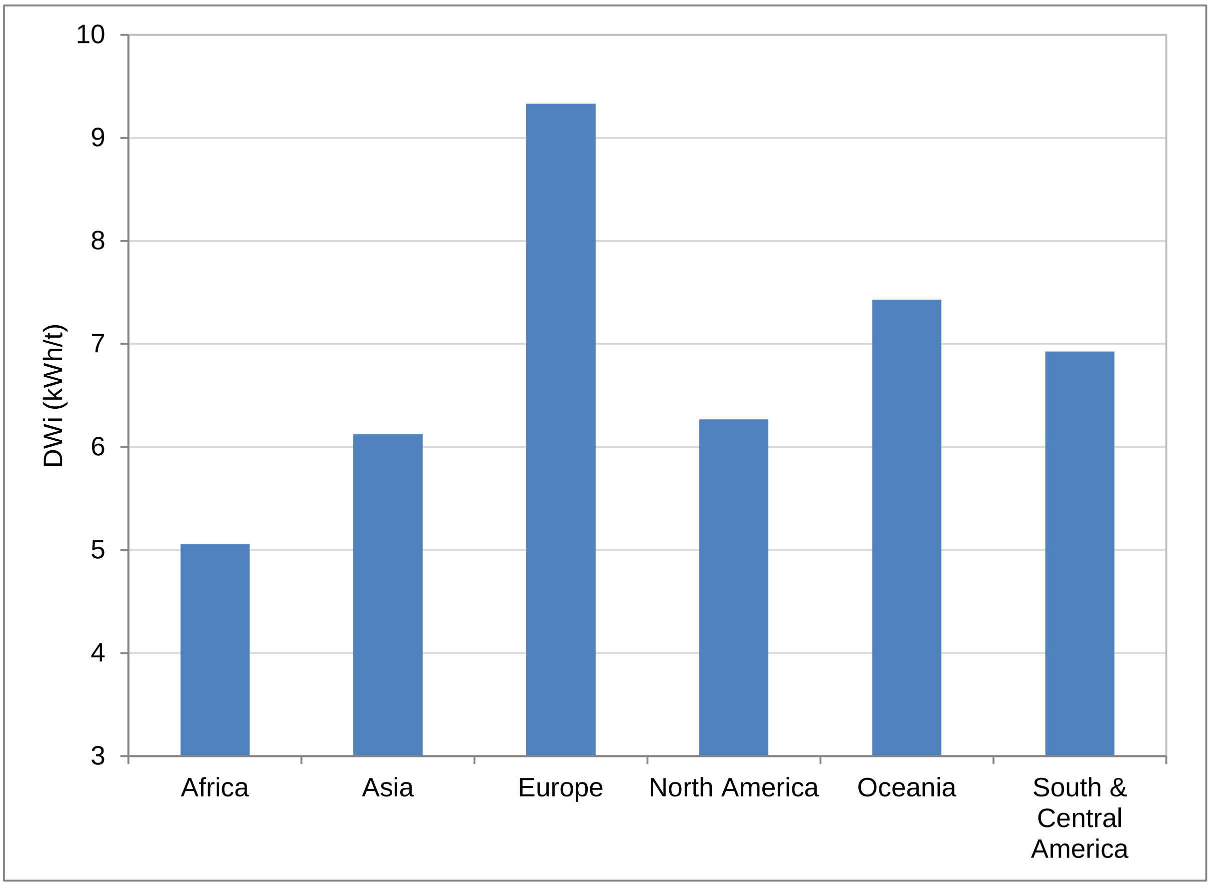

Figure 14 – Mean Copper Deposit DWi Values by Continent

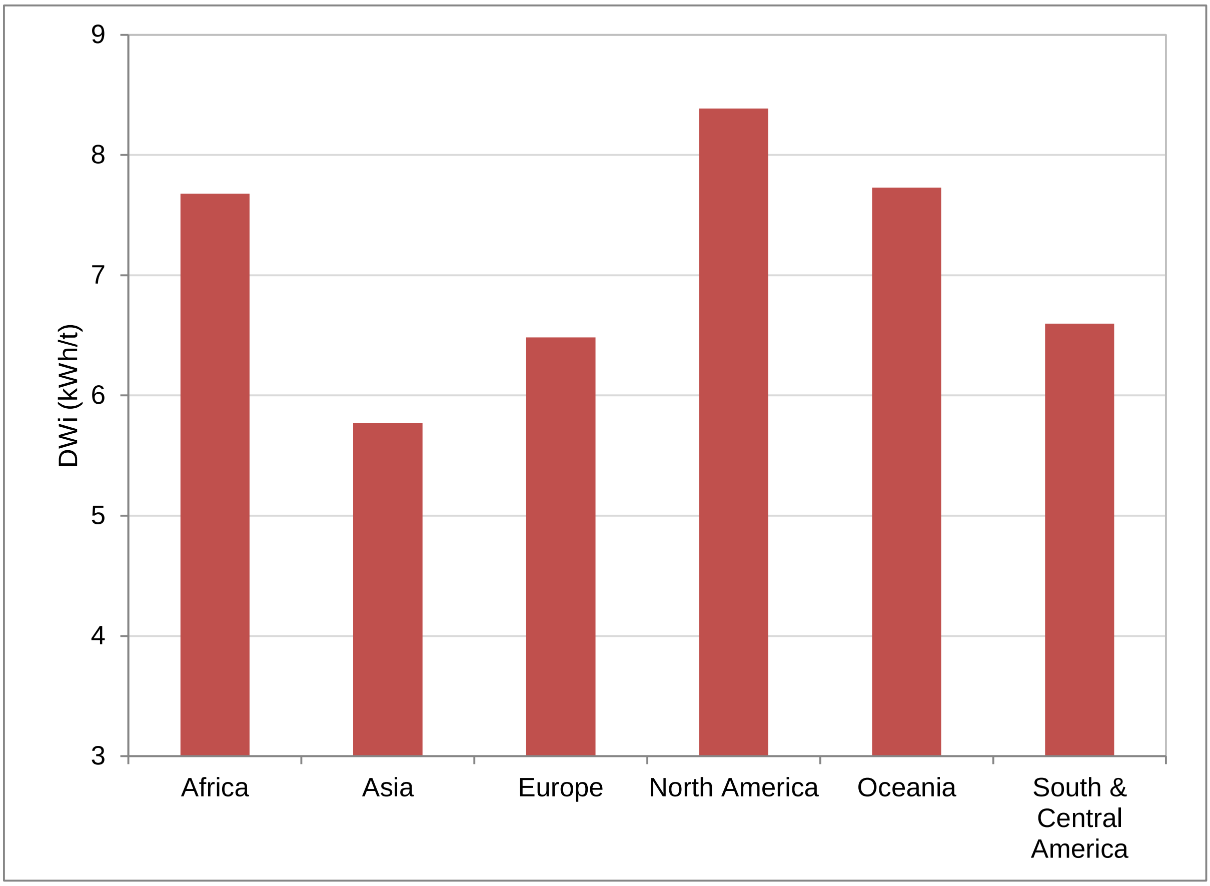

Figure 15 – Mean Gold Deposit DWi Values by Continent

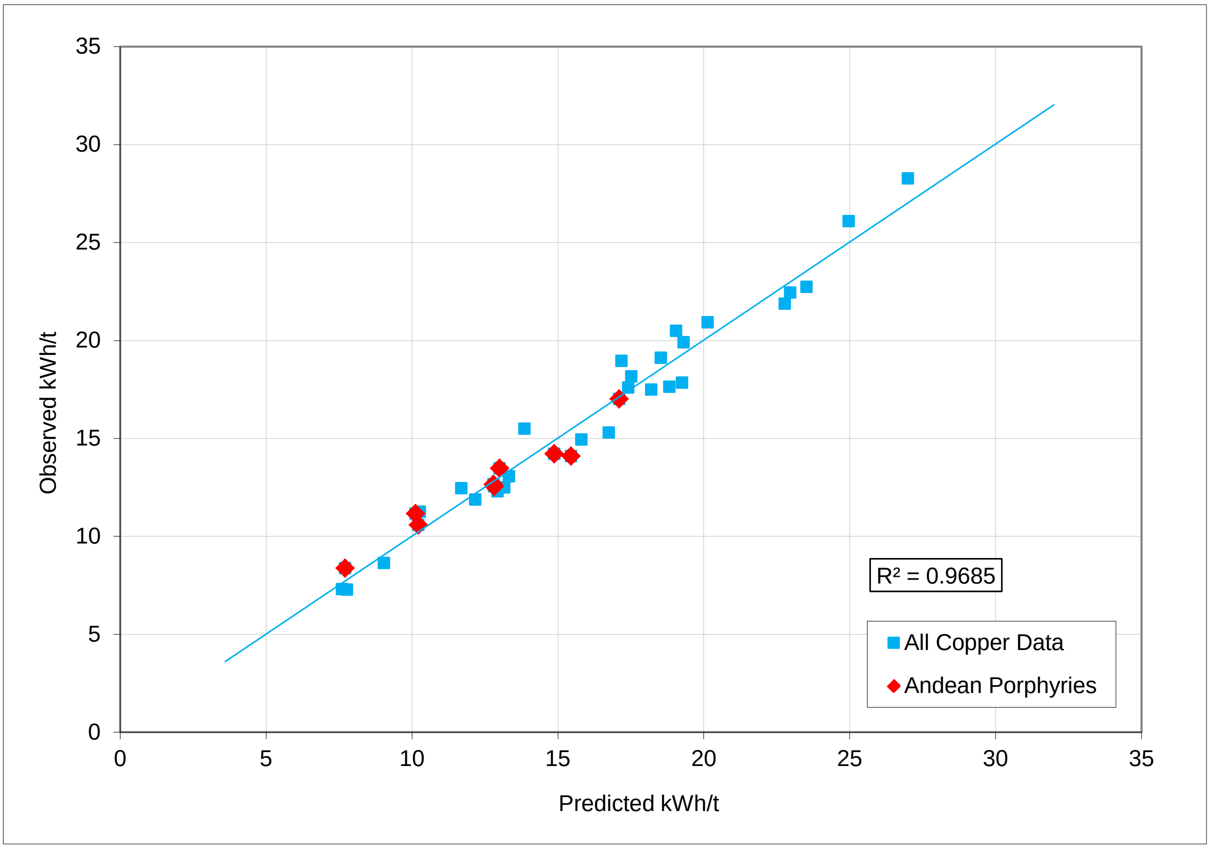

Figure 16 – Observed vs Predicted Comminution Specific Energy for Copper Circuits

CONCLUSIONS

To date over 35,000 SMC Tests have been carried out from over 1,300 deposits worldwide. These deposits are from 82 different countries and cover 30 different commodities. Hardness values were found to vary significantly from commodity to commodity. Similarly values varied from continent to continent mainly as a result of the different make-up of the commodities mined.

ACKNOWLEDGEMENTS

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APPENDIX 1 – COUNTRIES FROM WHICH SAMPLES HAVE HAD SMC TESTS CARRIED OUT ON THEM

Argentina
Armenia
Australia
Austria
Bolivia
Botswana
Brazil
Burkina Faso
Canada
Central African Republic
Chile
China
Colombia
Congo
Cote d'Ivoire
Democratic Republic of Congo
Ecuador
Egypt
Eritrea
Ethiopia
Fiji
Finland
Ghana
Greece
Greenland
Guatemala
Guinea
Guyana
India
Indonesia
Iran
Ireland
Kazakhstan
Kyrgyzstan
Laos
Lesotho
Liberia
Malawi
Mali
Mauritania
Mexico
Mongolia
Morocco
Mozambique
Namibia
New Zealand
Nicaragua
Niger
Nigeria
Pakistan
Panama
Papua New Guinea
Peru
Philippines
Poland
Portugal
Romania
Russia
Saudi Arabia
Senegal
Serbia
Sierra Leone
South Africa
South Korea
Spain
Suriname
Sweden
Tajikistan
Tanzania
Thailand
Turkey
Ukraine
United Kingdom
Uruguay
USA
Uzbekistan
Venezuela
Vietnam
Zambia
Zimbabwe

APPENDIX 2 – PRIMARY COMMODITY CONTAINED IN ORE SAMPLES WHICH HAVE HAD SMC TESTS CARRIED OUT ON THEM

Basalt
Bauxite
Bentonite
Coal
Cobalt
Copper
Diamond
Fluorspar
Gold
Graphite
Hematite
Iodine
K-Feldspar
Lead
Lithium
Magnetite
Manganese
Molybdenum
Nickel
Niobium
PGM
Phosphate
Rare Earths
Silver
Tin
Titanium
Tungsten
Uranium
Vanadium
Zinc