TABLE 21-15 Average Work Indices for Various Materials*

Material	No. of tests	Specific gravity	Work index†	Material	No. of tests	Specific gravity	Work index†
All materials tested	2088	—	13.81	Taconite	66	3.52	14.87
Andesite	6	2.84	22.13	Kyanite	4	3.23	18.87
Barite	11	4.28	6.24	Lead ore	22	3.44	11.40
Basalt	10	2.89	20.41	Lead-zinc ore	27	3.37	11.35
Bauxite	11	2.38	9.45	Limestone	119	2.69	11.61
Cement clinker	60	3.09	13.49	Limestone for cement	62	2.68	10.18
Cement raw material	87	2.67	10.57	Manganese ore	15	3.74	12.46
Chrome ore	4	4.06	9.60	Magnesite, dead burned	1	5.22	16.80
Clay	9	2.23	7.10	Mica	2	2.89	134.50
Clay, calcined	7	2.32	1.43	Molybdenum	6	2.70	12.97
Coal	10	1.63	11.37	Nickel ore	11	3.32	11.88
Coke	12	1.51	20.70	Oil shale	9	1.76	18.10
Coke, fluid petroleum	2	1.63	38.60	Phosphate fertilizer	3	2.65	13.03
Coke, petroleum	2	1.78	73.80	Phosphate rock	27	2.66	10.13
Copper ore	308	3.02	13.13	Potash ore	8	2.37	8.88
Coral	5	2.70	10.16	Potash salt	3	2.18	8.23
Diorite	6	2.78	19.40	Pumice	4	1.96	11.93
Dolomite	18	2.82	11.31	Pyrite ore	4	3.48	8.90
Emery	4	3.48	58.18	Pyrrhotite ore	3	4.04	9.57
Feldspar	8	2.59	11.67	Quartzite	16	2.71	12.18
Ferrochrome	18	6.75	8.87	Quartz	17	2.64	12.77
Ferromanganese	10	5.91	7.77	Rutile ore	5	2.84	12.12
Ferrosilicon	15	4.91	12.83	Sandstone	8	2.68	11.53
Flint	5	2.65	26.16	Shale	13	2.58	16.40
Fluorspar	8	2.98	9.76	Silica	7	2.71	13.53
Gabbro	4	2.83	18.45	Silica sand	17	2.65	16.46
Galena	7	5.39	10.19	Silicon carbide	7	2.73	26.17
Garnet	3	3.30	12.37	Silver ore	6	2.72	17.30
Glass	5	2.58	3.08	Sinter	9	3.00	8.77
Gneiss	3	2.71	20.13	Slag	12	2.93	15.76
Gold ore	209	2.86	14.83	Slag, iron blast furnace	6	2.39	12.16
Granite	74	2.68	14.39	Slate	5	2.48	13.83
Graphite	6	1.75	45.03	Sodium silicate	3	2.10	13.00
Gravel	42	2.70	25.17	Spodumene ore	7	2.75	13.70
Gypsum rock	5	2.69	8.16	Syenite	3	2.73	14.90
Ilmenite	7	4.27	13.11	Tile	3	2.59	15.53
Iron ore	8	3.96	15.44	Tin ore	9	3.94	10.81
Hematite	79	3.76	12.68	Titanium ore	16	4.23	11.88
Hematite—specular	74	3.29	15.40	Trap rock	49	2.86	21.10
Oolitic	6	3.32	11.33	Uranium ore	20	2.70	17.93
Limanite	2	2.53	8.45	Zinc ore	10	3.68	12.42
Magnetite	83	3.88	10.21				

*Allis-Chalmers Corporation.
†Caution should be used in applying the average work index values listed here to specific installations since individual variations between materials in any classification may be quite large.

grinding equipment apply forces in different ways, and this makes them better suited to particular classes of materials. Figure 21-131 lists the modes of particle loading as they occur in industrial mills. This loading can take place either by slow compression between two planes or by impact against a target. In these cases the force is normal to the plane. If the applied normal forces are too weak to affect the whole of the particle and are restricted to a partial volume at the surface of the particle, the mode is attrition. An alternative way of particle loading is to apply a shear force by moving the loading planes horizontally. The table indicates that compression and impact are used more for coarse grinding, while attrition and abrasion are more common in fine and superfine grinding.

Hard materials (especially Mohs hardness 7 and above) are usually ground by devices designed for abrasion/attrition modes. For example, roll mills would rarely, if ever, be used for grinding of quartz, but media mills of various sorts have been successfully used to grind industrial diamonds. This is so primarily because both compression and high-energy impact modes have substantial contact between the mill and the very hard particles, which causes substantial wear of the device. Many attrition and abrasion devices, however, are designed so that a large component of grinding occurs by impact of particles on one another, rather than impact with the device. Wear still occurs, but it's less dramatic than with other devices.

Ductile materials are an especially difficult problem for most grinding devices. Almost all grinding devices are designed for brittle materials and have some difficulties with ductile materials. However, devices with compression or abrasion modes tend to have the greatest difficulty with these kinds of materials. Mills with a compression mode will tend to flatten and flake these materials. Flaking can also occur in mills with a tangential abrasion mode, but smearing of the material across the surface of the mill is also common. In both cases, particle agglomeration can occur, as opposed to size reduction. Impact and attrition devices tend to do somewhat better with these materials, since their high-speed motion tends to cause more brittle fracture.

Conversely, mills with impact and attrition modes often do poorly with heat-sensitive materials where the materials become ductile as they heat up. Impact and attrition mills cause significant heating at the point of impact, and it is not uncommon for heat-sensitive materials (e.g., plastics) to stick to the device rather than being ground. In the worst cases, cryogenic grinding can be necessary for highly ductile or heat-sensitive materials.

Grindability Methods Laboratory experiments on single particles have been used to correlate grindability. In the past usually it has been assumed that the total energy applied could be related to the grindability whether the energy is applied in a single blow or by repeated dropping of a weight on the sample [Gross and Zimmerly, *Trans. Am. Inst. Min. Metall. Pet. Eng.* **87:** 27, 35 (1930)]. In fact, the results depend on the way in which the force is applied (Axelson, Ph.D. thesis, University of Minnesota, 1949). In spite of this, the results of large mill tests can often be correlated within 25 to 50 percent by a simple test, such as the number of drops of a particular weight needed to reduce a given amount of feed to below a certain mesh size. Two methods having particular application for coal are known as the *ball-mill* and *Hardgrove* methods. In the ball-mill method, the relative amounts of energy necessary to pulverize different coals are determined by placing a weighed sample of coal in a ball mill of a specified size and counting the number of revolutions required to grind the sample so that 80 percent of it will pass through a no. 200 sieve. The grindability index in percent is equal to 50,000, divided by the average of the number of revolutions required by two tests (ASTM designation D-408).

In the Hardgrove method, a prepared sample receives a definite amount of grinding energy in a miniature ball-ring pulverizer. The unknown sample is compared with a coal chosen as having 100 grindability. The Hardgrove grindability index = $13 + 6.93W$, where W is the weight of material passing the no. 200 sieve (see ASTM designation D-409).

Chandler [*Bull. Br. Coal Util. Res. Assoc.* **29**(10): 333 and **29**(11): 371 (1965)] finds no good correlation of grindability measured on 11 coals with roll crushing and attrition, and so these methods should be used with caution.