Crushing Tests by Pressure and Impact

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Compression Tests

The standard method of determining the crushing resistance of rocks consists of crushing prepared shapes under slow compression, and expressing the ultimate crushing resistance at the load causing failure in pounds per square inch of cross-sectional area perpendicular to the crushing force, with the height approximately equal to the diameter. One-inch cubes or cylindrical drill cores are commonly used.

Cubes and drill cores are cut by a high-speed steel disk with diamond dust embedded in the edges, and running under a water spray. Such a saw will cut one square inch or more of hard stone per minute.

An oiled, spherical, swivel compression block of small diameter should be used to equalize the pressure. Each sample is crushed between sheets of cardboard or blotting paper extending about one-half inch beyond the edges of the stone. A cloth is wrapped around it to prevent dangerous explosive shattering. It is probably preferable to place the swivel block below the specimen, with either a rigid head or another swivel block above. Whatever the arrangement, the conditions should be selected that will develop the maximum crushing strength of the specimen, even though its top and bottom planes may not be precisely parallel.

The cardboard pads may be dispensed with if the ends of the specimens are polished smooth. The use of lead pads was discontinued because of the observed tendency to split the material.

The samples are weighed and measured before breaking, and the density is calculated.

Cubes that contain bedding planes or veinlets are usually placed with these vertical and parallel to the crushing force, in order to develop the maximum resistance possible.

A number of compression tests were made on Canadian ores, by Forrest Nagler, of the Allis-Chalmers Manufacturing Co., and are listed alphabetically in Table 1. These tests were made on one-inch cubes or on diamond-drill cores approximately one inch in diameter and one inch long. The drill cores represent virgin rock, while the cubes may have been previously weakened by explosives.

Compression tests have been made in the Allis-Chalmers Milwaukee Laboratory on a number of ores and other materials. These are listed alphabetically in Table 2.

In test No. 1339, on limestone from the Hanna Coal Co., comparison was made between 2 by 2-in. diamond-drill core segments and one-inch cubes cut from the cores in the same strata. Results for the cylinders are tabulated directly below those for the cubes. The bedding planes were normal to the compressive force in breaking the cylinders and parallel in breaking the cubes, which accounts for the lower strength obtained from the cylinders.

The percentage of net linear compression at the ultimate pressure was measured in test No. 1055 for Fontana TVA quartzite as 0.30 for cube A, and 0.37 for cube D.

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In test No. 1082, for Clifton Magnetite, it was measured as 0.40 for cube A, 0.50 for cube C, and 0.36 for cube D.

TABLE 1.—*Compression Tests on Canadian Ores*

Mine and District	Mineral	Specific Gravity	Shape	Compressive Strength, Thousands Lb. per Sq. In.		
				Spec. A	Spec. B	Spec. C
Aldermac Copper, Noranda	Pyrite		Cube	22.4	20.2	
Arntfield Gold, Noranda	Light green	2.86	Cube	13.8	14.9	
Beattie Gold, Quebec	No. 1	2.68	Cyl.	16.7	31.6	
	No. 2	2.78	Cyl.	40.5		
	No. 3	2.73	Cyl.	24.2	29.6	
Cariboo Gold, B. C.		2.94	Cyl.	26.8	14.3	
		2.99	Cube	33.0		
Cons. M. and S., East B. C.	No. 1	2.89	Cyl.	20.3		
	No. 2	2.89	Cyl.	60.1	65.0	45.7
East Malartic, Malartic		2.65	Cube	41.5	44.1	
	Diorite	2.91	Cube	10.2	28.2	
	Feldspar porphyry	2.65	Cube	34.2		
	Altered porphyry		Cube	23.5		
	Graywacke	2.67	Cube	38.6	20.9	32.9
	Greenstone	3.06	Cube	2.5	5.1	6.7
Gold Eagle, Red Lake	Granodiorite	2.68	Cyl.	20.4	20.3	19.3
Gurney Gold, N. Manitoba	Siliceous tuff	3.02	Cube	46.7		
	Siliceous tuff	2.87	Cube	35.1		
	Siliceous tuff	2.64	Cube	38.8		
	Greenstone	2.92	Cube	32.3		
	Chert	2.65	Cube	37.2		
	Quartz ore	2.98	Cube	25.3		
Howey Gold, Red Lake	Wall rock	2.71	Cyl.	26.9	23.5	21.4
	Dike III	2.68	Cyl.	25.6	30.0	19.2
	Vein	2.63	Cyl.	18.8	14.6	11.7
	Waste	2.74	Cyl.	19.0	17.8	16.9
Inco, Creighton, Sudbury	Norite I	2.65	Cyl.	32.9	29.2	
	Norite II	2.86	Cyl.	23.7	20.1	
	Gabbro I	3.00	Cyl.	30.5	36.4	
	Gabbro II	3.13	Cyl.	44.2	27.6	
	Granite	2.69	Cyl.	28.5		
Inco, Frood, Sudbury	Rhyolite	2.69	Cyl.	44.5	32.6	
	Gabbro I	3.03	Cyl.	18.2	18.9	
	Gabbro II	3.09	Cyl.	38.1	33.6	
	Quartzite I	2.71	Cyl.	24.1	20.9	
	Quartzite II	2.77	Cyl.	30.4	27.8	
Inco, Levack, Sudbury	Norite	2.77	Cyl.	23.7	23.4	
	Granite	2.47	Cyl.	37.3	37.4	
Kelowna Ex., B. C.		2.89	Cube	36.0	38.0	
Lebel Oro, Kirkland Lake	Dark wall	2.77	Cyl.	15.0		
	Light wall	2.63	Cyl.	48.3	51.2	38.1
Little Long Lac, Long Lac	Wall rock I	2.71	Cyl.	12.5	12.4	
	Wall rock II	2.72	Cyl.	19.0	19.5	
	Wall rock III	2.71	Cyl.	10.2	16.0	
	Ore IV	2.80	Cyl.	17.7	10.8	
	Wall rock V	2.77	Cyl.	12.3	9.0	14.9
Macassa, Kirkland Lake			Cube	24.8	29.7	
	Porphyry		Cyl.	61.3		
	Syenite		Cyl.	40.2	32.3	31.0
	Black lamp		Cyl.	32.6	30.6	
			Cyl.	52.3	39.0	20.7
	Syenite porphyry	2.62	Cube	29.5		
	Lamp porphyry	2.77	Cube	24.2	21.6	
McQuaig, Red Lake	Ore	2.96	Cyl.	7.4	8.6	9.5
Ontario Rock, Ontario	Trap	3.01	Cube	27.6		
	Soft cast iron	7.00	Cube	74.8		
	Soft cast iron	7.00	Cube	70.9		
Osoyoos Ltd., B. C.		4.51	Cube	24.9		
		3.99	Cube	37.7		

The compressive strengths and other physical properties of many typical American rocks have been tabulated and published.[1] The highest ultimate compressive stress of any rock in this tabulation is a chert from Joplin, Mo., at 86,300 lb. per square inch.

It is evident from these data that determinations of compressive strength, while valuable, do not furnish an entirely satisfactory criterion for crusher installations. The variations between duplicate

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[1] References are at the end of the paper.

TABLE 2.—*Compression Tests*[a]

Test No.	Name and Location	Material	Specific Gravity	Compressive Strength, Thousands Lb. per Sq. In.			
				Spec. A	Spec. B	Spec. C	Spec. D
1406	Arizona Sand and Rock Co., Phoenix, Ariz.	Gravel	2.6	34.2	27.3	24.0	30.4
1552	A. S. & R. Co., Tacoma, Wash.	Limestone	2.74	20.8	14.7	17.2	14.9
				22.6	10.0	12.4	19.3
				18.8	16.1		
1171	Big Rock Stone, Arkansas	Blue granite	2.58	24.2	24.2	20.6	17.2
		Gray granite	2.50	15.1	12.3	12.3	10.7
		Quartzite	2.63	29.2	26.1	19.4	
1578	Calif. Rock and Gravel, California	Trap rock	2.86	15.8	18.8	17.3	20.1
				16.2	19.0		
1407	Champion Spark Plug Co., Detroit, Mich.	Andalusite	3.08	11.8	11.0	7.8	
		Dumortierite	3.21	51.6	38.2	36.9	
755	Champion Spark Plug Co., Nevada	Dumortierite	3.21	26.1	32.5		
1205	Climax Molybdenum Co., Climax, Colo.	Molybdenum ore	2.64	16.5	15.6	19.1	15.7
1506	Climax Molybdenum Co., Climax, Colo.	Molybdenum ore	2.62	17.9	29.1	26.7	17.8
				18.2	17.7	18.7	17.6
				21.7	14.4		
1396	Correale Construction Co., Minersville, Pa.	Granite and shale	2.66	7.8	6.4	9.0	8.2
				7.9	9.1	8.3	
1285	Construction Service, Massachusetts	Limestone		32.8	29.3	38.0	33.1
1220	Dann and Wendt, Wisconsin	Dolomite	2.31	4.0	8.2	4.4	5.0
1191	Emsco Refractories, Salt Lake City, Utah	Quartz	2.63	23.6	36.4	31.6	
1055	Fontana TVA, Tennessee	Quartzite	2.65	21.0	31.7	19.3	19.4
1571	Globe Iron Co., Iron Mt., Mich.	Specular hematite	2.90	35.1	36.0	25.0	38.6
				38.4	25.4		
1487	Great Western Sugar Co., Horse Creek, Wyo.	Limestone	2.6	30.0	25.9	27.4	
1271	Hanna Coal Co., Ohio	Limestone	2.56	16.5	20.7	15.9	15.5
		Limestone massive	2.68	39.2	27.5	34.9	
1339	Hanna Coal Co., Ohio	Limestone					
		1-in. cube	2.51	12.2	7.5	11.0	25.9
		2-in. cyl.	2.51	16.8	6.7	6.9	22.8
		1-in. cube	2.60	17.3	22.1	20.2	
		2-in. cyl.	2.60	15.5	15.2	13.3	
1082	Hanna Ore Co., DeGrasse, N. Y.	Magnetite	3.97	23.1	17.6	18.0	23.1
1397	Hanna Ore Co., DeGrasse, N. Y.	Magnetite	4.19	19.7	22.9	20.6	29.7
			4.35	24.6	28.4		
1469	Helena Sand and Gravel Co., Helena, Mont.	Trap rock	2.81	20.8	16.6	19.4	
1312	McFeely Brick, Pennsylvania	Ganister	2.55	32.9	34.2	36.6	
1318	Missouri Portland Cement, Batesville, Ark.	Limestone	2.66	21.5	17.2	16.7	23.5
				22.1	16.3	24.5	22.4
				17.9	17.5		
1345	Missouri Portland Cement, St. Louis, Mo.	Limestone	2.63	15.6	17.2	18.1	13.5
1324	Missouri Lime Co., St. Genevieve, Mo.	Limestone	2.65	15.4	13.8	16.0	11.2
				15.2	10.8	9.7	
1145	Mullite Refractories, Connecticut	Kyanite	3.71	51.0	55.8	56.6	46.1
1515	Oliver Iron Mining Co., Tower, Minn.	Jasper		60.0	32.1	42.3	42.2
				35.0			
		Hematite Level 12	4.85	26.5	36.2	46.7	39.7
		Store 667		50.2	26.2		
		Level 15		33.5	33.7	41.8	43.0
		Alaska stope		42.8	31.4		
		Level 17, Stope 734		33.1	41.6	30.4	
		Level 19, Stope 734		29.3	21.3	17.5	24.4
		Level 21, Stope 651		36.2	48.9	45.8	36.2
				37.8	50.7		
1402	Petoskey Portland Cement Co., Petoskey, Mich.	Limestone, fine	2.58	15.5	13.4	13.8	
		Limestone, coarse	2.64	16.9	13.3	17.9	19.1
1456	Reserve Mining Co., Babbitt, Minn.	Taconite	3.16	34.0	40.4	42.7	41.1
				48.6			
1039	Soudan Mine, Minnesota	Iron ore	5.13	57.2	58.8	66.0	78.8
1298	Southwest Stone, Oklahoma	Limestone	2.62	13.7	21.8		
	Texas	Trap rock 2	2.90	25.0	22.6	20.5	32.4
1227	Spokane Idaho, Idaho	Lead ore	4.05	22.8			
1147	Steep Rock, Ontario	Hematite	3.89	41.1	34.0	22.1	
1611	Superior Stone Co., Red Hill, Va.	Granite	2.82	13.6	12.5	16.2	17.2
				15.5			
1138	Trap Rock Corp., Minnesota	Trap rock	2.98	34.1	33.5		
		Granite	2.85	25.6	33.5	32.7	27.3
		Red granite	2.62	41.1	39.0		
1159	Tungsten Metals, Eli, Nev.	Limestone	2.64	15.3	11.4		
1347	Western-Brooker, Georgia	Granite	2.70	13.2	17.1	24.0	27.0
				17.7	18.7	19.0	14.1
1291	W. G. Swart, Minnesota	Magnetic taconite		52.8			

[a] All tests on one-inch cubes except No. 1339, for which two tests were made on cylinders.

samples are very large, and the preparation of the cubes is somewhat laborious, so that the number of specimens broken is usually small. While the power consumption and capacity are based upon the average crushing resistance, the crusher construction must be based upon the hardest specimen tested, and since different pieces of rock exhibit such wide differences in crushing resistance, the variety that ultimately breaks the crusher may well escape testing. Moreover, the maximum velocity of the crusher jaws approaches that of an impact, with concentration of stresses at contact points, and with other conditions very dissimilar to those obtaining in a compression test. It has been shown, for instance, that an increase in the velocity of hit causes an important increase in the amount of fine material produced.[2] For these reasons considerable attention has been devoted to the development of a suitable device for testing impact crushing.

IMPACT TESTS

The development of a method of measuring the crushing resistance of rock under impact has followed a definite pattern in the Allis-Chalmers Laboratory. It was decided about 10 years ago to avoid the customary drop-weight methods, on the ground that transmission of a portion of the energy of impact through the sample of the supports is undesirable. As a result, three different types of pendulum devices have been developed.

The first of these was constructed in 1934.[3] It consisted of a special head attached to an Amsler impact testing machine, arranged so that in breaking a standard test bar by impact the energy of the falling pendulum was divided between that required to break the standard bar and that required to crush a sample of stone placed under a piston in the pendulum. The sample used consisted of 10 grams of screen-sized particles, which were screen-analyzed after impacting, and a calculation was made of the net energy required to produce a unit surface area.

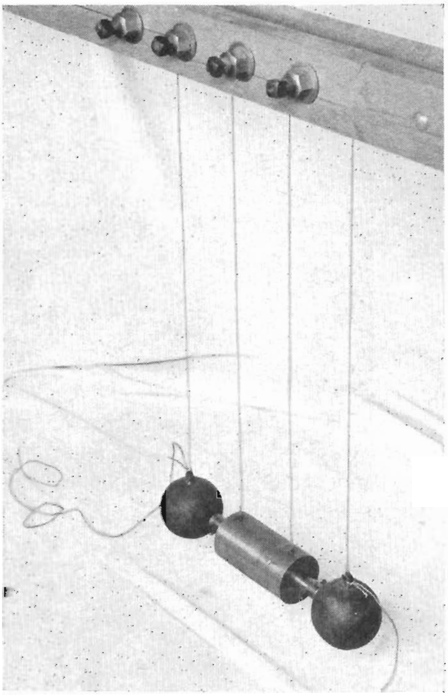

FIG. 1.—TWIN-BALL PENDULUM IMPACT DEVICE.

However, in this apparatus some deflection of the bar supporting the piston was unavoidable during impact, and it was replaced early in 1938 by the first twin-ball pendulum impact device (Fig. 1).

In this machine 10 grams of screen-sized sample were crushed between two hardened steel pistons struck simultaneously by two steel balls (each 3-in. diameter) released by cutting a cord.

This device was much more convenient and practical than the first, and by its use measurement was made of the impact energy required to produce new surface area, in terms of joules per square meter, for several ores and other materials, some of which are listed in Table 3.

From these results it is calculated

that the laboratory ball mill used in making the standard grindability tests[4] does 52 joules of useful work in producing new surface per revolution, while the measured total energy input to the mill is 93 joules per revolution. This is equivalent to a relative grinding efficiency in the mill of 56 per cent.

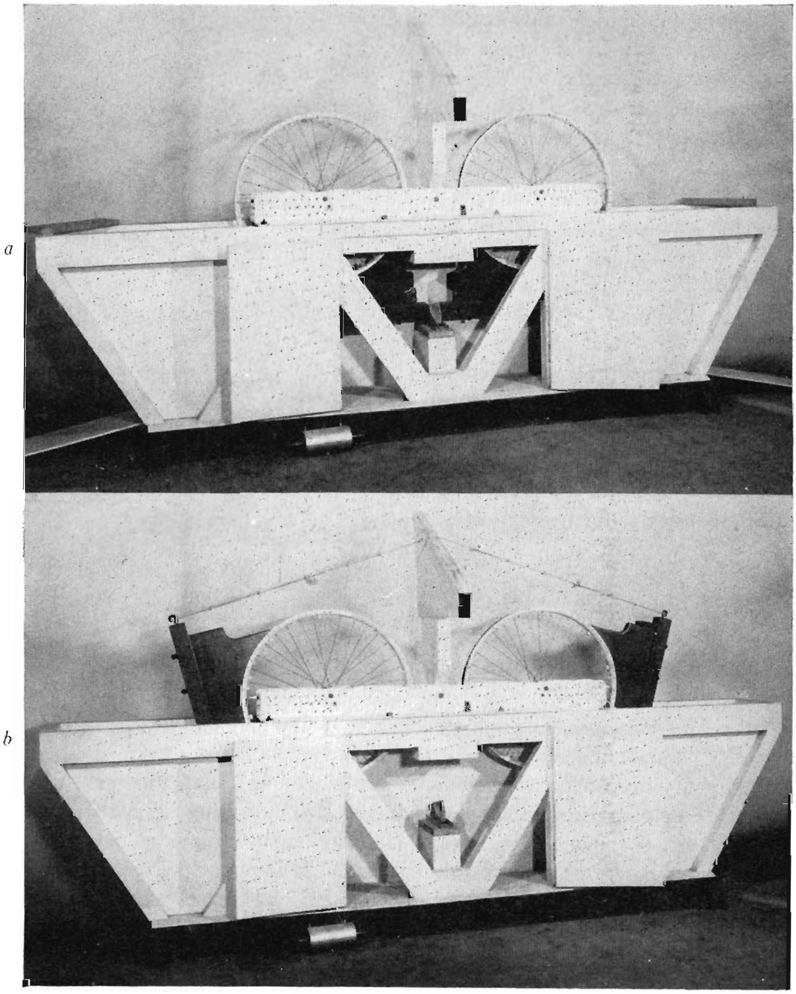

FIG. 2.—PENDULUM IMPACT DEVICE USED IN BASIC INDUSTRIES LABORATORY, ALLIS-CHALMERS MANUFACTURING COMPANY.
a, at rest; *b*, in operation.

The impact device used at present is shown in Fig. 2. It consists of two standard 22-in. front bicycle wheels, each reinforced with a steel band encircling the wheel and carrying identical steel hammer bars 2 in. square in cross section, 28 in. long, and weighing approximately 30 lb. The center of each bar is 16 in. below the axles of the wheels, which are mounted in line in a frame, so that when they are at rest the ends of the suspended horizontal hammer bars are separated by the thickness of the specimen to be crushed between them. This free distance between the hammers is adjustable from 0 to 12 in., and is set at 2 in. in the tests to be described. The Brinnell hardness of the hammers is 230.

TABLE 3.—*Impact Energy Required to Produce New Surface Area*

Test No.	Name of Investigator	Location of Test	Material	Surface Energy, Joules per Sq. Meter
695	P. T. Williams	Portugal	Gold ore	289
684	Phelps Dodge	Ajo, Ariz.	Copper ore	296
732	Cement Assn.	Chicago	Portland cement Clinker Q	300
570	Little Long Lac	Ontario	Gold ore	307
732	Cement Assn.	Chicago	Portland cement Clinker Q	322
799	Kerr-Addison	Ontario	Gold ore	403
504	Springs mines	East Rand, S. Afr.	Gold ore	462
700	Aluminum Co.	Alcoa, Tenn.	Petroleum coke	760
554	Monsanto	St. Louis	Pyrite	900

The ends of the hammers opposite the striking ends carry hooks. In operation, the two hooks are connected by a cord, which passes up over both wheels and over an adjustable block of wood separating the two wheels, so that both hammers may be raised above the specimen by an equal amount, as indicated by degree graduations on each wheel and pointers on the frame.

When the hammers have both been adjusted to the desired setting, the cord is cut and they fall freely to strike simultaneous blows on opposite sides of the specimen. There is usually very little rebound when the stone is broken, and its vertical component is practically negligible.

Where B is the angle of fall of each pendulum, the total impact energy E in foot-pounds is equal to a constant K times haversine B and the horizontal impact velocity V is equal to a constant K_2 times haversine B. For the hammers now in use K_1 equals 164 and K_2 equals 11.8. At 20 foot-pounds, V equals 4.1 ft. per second.

In the standard method of testing only broken pieces that pass a 3-in. square opening and are retained on a 2-in. square opening are used. Slabby or acicular pieces are discarded. If the longest dimension is designated as A, the longest dimension perpendicular to A as B, and the longest dimension perpendicular to both A and B as C; the specimen is placed in the holder in such a position that the hammers strike on both sides of dimension C, which is measured in inches with calipers before each blow. Deductions are made for any small projections along C.

In evaluating a material, 10 or more pieces are broken when available. The first piece is tested with a low-energy blow, and the height of fall is gradually increased until the specimen breaks into two or more pieces of approximately equal size. Each succeeding piece is first tested with an energy slightly under that required to break the preceding piece, and the height of fall is increased so that the specimen is broken after two or three blows. The energy increment between successive blows is regularly 4 ft-lb. The maximum energy obtainable with the device is approximately 150 foot-pounds.

The results are expressed as the impact crushing strength per inch of thickness (dimension C), or as foot-pounds per inch. Both the average and the maximum results are reported.

The results of tests on 72 different materials are summarized in Table 4. They are listed in the order of increasing average hardness, or of increasing resistance to impact crushing, in foot-pounds per inch.

TABLE 4.—*Impact Tests*

Test No.	Name and Location	Material	Specific Gravity	Number of Pieces Broken	Ft-lb. per In.	
					High	Average
1519	Lawrence Portland Cement Co., Thomaston, Maine	Cement clinker	3.15	10	9.88	3.07
1536	Pennsylvania Salt Mfg. Co., Natrona, Pa.	Siderite		10	8.6	3.48
1513	A. C. Bateman, Johannesburg, S. A.	Limestone	2.6	8	7.7	3.55
1536	Pennsylvania Salt Mfg. Co., Natrona, Pa.	Cryolite		10	5.9	3.82
1516	Saticoy Rock Co., Saticoy, Calif.	Granite pebbles	2.6	7	7.3	4.73
1394	St. Claire Lime, Oklahoma City, Okla.	Limestone	2.6	10	8.2	5.00
1341	Portage Manly Sand, Portage, Wis.	Sandstone	2.6	2	6.4	5.22
1536	Pennsylvania Salt Mfg. Co., Natrona, Pa.	Silica and fluorspar		10	9.6	5.27
1379	William Knight, North Carolina	Magnetite	4.77	10	7.6	5.60
1377	Republic Steel, Spaulding, Ala.	Fe_2O_3, fine	3.30	5	10.8	5.70
1402	Petoskey P.C.C., Petoskey, Mich.	Fine limestone	2.58	9	12.0	6.09
1407	Champion Spark Plug, Detroit, Mich.	Aydalusite	3.08	10	8.0	6.18
1324	Mississippi Lime Co., St. Genevieve, Mo.	White limestone	2.6	4	7.8	6.28
1484	Southwest Stone Co., Chico, Tex.	White limestone	2.68	12	10.3	6.31
1377	Republic Steel, Spaulding, Ala.	Fe_2O_3, coarse	3.29	6	10.8	6.58
1416	LeClede Christy, St. Louis, Mo.	Calcined kyanite ore	2.89	10	9.8	6.62
1516	John D. Gregg, Roscoe, Calif.	Granite pebbles	2.6	9	11.8	7.07
1345	Missouri Portland Cement Co., St. Louis, Mo.	Limestone	2.6	11	12.1	7.18
1613	DuPont, Terre Haute, Ind.	Pyrite in coal	3.6	12	16.0	7.55
1567	Cedar Bluff Stone Co., Princeton, Ky.	Limestone	2.6	10	11.3	7.97
1516	Graham Bros. Inc., El Monte, Calif.	Granite pebbles	2.6	14	19.3	8.37
1384	Loomis Talc Co., Coveneua, N. Y.	Talc	2.83	4	11.4	8.55
1388	Jones and Laughlin, Star Lake, N. Y.	Iron ore	5	11	15.5	9.84
1334	Southern Ferr Chattanooga, Tenn.	Ferrosilicon	6	5	14.8	10.16
1366	Wisconsin Steel, Nashwauk, Minn.	Hard ore	4.20	8	21.7	10.16
1497	Southern Stone Co., Springtown, Okla.	Limestone	2.6	10	18.8	10.47
1533	General Crushed Stone Co., Auburn plant	Limestone	2.6	10	19.5	10.74
1480	Southwest Stone Co., Knippa, Tex.	Black trap rock	3.12	12	16.0	10.90
1406	Arizona Sand and Rock, Phoenix, Ariz.	Pebbles	2.6	10	17.7	11.14
1611	Superior Stone Co., Red Hill, Va.	Granite	2.82	10	13.4	11.20
1347	Western and Brooker, Camak, Ga.	Granite	2.6	7	14.8	11.42
1358	Union Steel Castings, Pittsburgh, Pa.	Fe-Mn-C alloy	7.21	2	15.5	11.55
1567	Cedar Bluff Stone Co., Princeton, Ky.	Limestone	2.6	10	15.5	11.60
1398	Icaza and Co., Panama	Limestone	2.6	10	17.3	11.66
1567	Cedar Bluff Stone Co., Princeton, Ky.	Limestone	2.6	10	16.0	12.07
1552	A. S. and R. Co., Tacoma, Wash.	Limestone	2.74	10	17.5	12.20
1487	Great Western Sugar Co., Horse Creek, Wyo.	Limestone	2.6	10	20.5	12.60
1367	Batesville White, Arkansas	Limestone	2.6	13	22.2	13.08
1324	Mississippi Lime Co., St. Genevieve, Mo.	Gray limestone	2.6	4	19.7	13.16
1412	Cold Springs, Granite, Minn.	Pink granite	2.6	3	13.6	13.48
1536	Pennsylvania Salt Mfg. Co., Natrona, Pa.	Granite	2.6	10	18.0	13.65
1560	Climax Molybdenum Co., Climax, Colo.	Molybdenum ore	2.62	10	19.4	14.09
1427	Oliver Iron Mining, Tower, Minn.	Jasper	3.42	10	25.2	14.51
1412	Concrete Materials, Sioux Falls, S. D.	Granite	2.6	10	18.7	14.54
1469	Helena Sand-Gravel Co., Helena, Mont.	Trap rock	2.81	7	24.0	14.69
1402	Petoskey P.C.C., Petoskey, Mich.	Coarse limestone	2.63	9	27.0	14.75
1398	Icaza and Co., Panama	Sandstone	2.6	8	22.1	14.88
1396	Correale Const. Co., Minersville, Pa.	Shale	2.66	10	22.1	15.06
1567	Cedar Bluff Stone Co., Princeton, Ky.	Limestone	2.6	10	19.0	15.35
1397	Hanna Ore Co., DeGrasse, N. Y.	Iron ore	4.24	8	23.4	15.64
1372	TVA Fontana Dam, Tennessee	Limestone	2.6	9	30.5	15.96
1565	John T. Dyer (A-C Office), Harrisburg, Pa.	Gray granite	2.98	10	25.3	16.08
1502	W. S. Barry	Rhyolite olivine	2.65	10	21.1	16.11
1390	Old Colony Crushed Stone, Quincy, Mass.	Granite	2.61	9	28.7	16.59
1578	Calif. Rock and Gravel, California	Trap-rock gravel	2.8	10	28.8	16.74
1571	Globe Iron Co., Duluth, Minn.	Specular hematite	2.90	10	29.8	17.03
1318	Missouri Portland, Batesville, Ark.	Limestone	2.6	13	33.2	17.91
1318	Missouri Portland, St. Louis, Mo.	Limestone	2.6	13	23.8	18.00
1505	Koppers Company, Kobuta, Pa.	Al-Ni pigs	3.70	10	27.5	19.15
1456	Reserve Mining, Babbitt, Minn.	Taconite	3.16	20	36.6	19.88
1502	Lynn Sand and Stone, Co., Boston, Mass.	Gabbro diorite	2.85	10	29.8	20.07
1363	Great Notch Granule Co., Granule, N. J.	Trap rock		8	28.9	20.72
1412	Cold Springs Granite Co., Cold Springs, Minn.	Red granite	2.6	4	27.1	21.85
1412	Cold Springs Granite Co., Morton, Minn.	Granite	2.6	3	27.1	21.90
1412	L. G. Everist Co., Del Rapids, S. Dak.	Everist granite	2.6	8	28.5	22.20
1358	Union Steel Casting, Pittsburgh, Pa.	Fe-Mn alloy	6.84	2	34.1	25.20
1515	Oliver Iron Mining Co., Tower, Minn.	Hematite	4.85	15	34.0	25.29
1358	Union Steel Casting Co., Pittsburgh, Pa.	Si-Mn alloy	6.63	1	29.6	29.60
1427	Oliver Iron Mining Co., Tower, Minn.	Hematite	4.93	10	40.8	31.32
1412	Spencer Quarries Co., South Dakota	Red granite	2.6	2	33.9	32.00
1407	Champion Spark Plug, Detroit, Mich.	Dumortierite	3.21	10	60.2	38.10
1493	Vanadium Corp. of America, Niagara Falls, N. Y.	Chrome metal	7.36	4	73.8	55.45

TABLE 5.—*Comparison Tests*

Test No.	Material	State	Compression			Impact, Ft-lbs.	
			Cubes Broken	Lb. per Sq. In.		Maximum	Average
				Maximum	Average		
1402	Limestone (fine)	Mich.	4	15,450	14,220	12.0	6.09
1407	Andalusite	Mich.	3	11,800	10,207	8.0	6.18
1324	Limestone (white)	Mo.	2	10,830	10,285	7.8	6.28
1345	Limestone	Mo.	4	18,120	16,100	12.1	7.18
1406	Gravel	Ariz.	10	36,300	28,835	17.7	11.14
1611	Granite	Va.	5	17,200	15,020	13.4	11.20
1347	Granite	Ga.	9	27,600	17,923	14.8	11.42
1552	Limestone	Wash.	24	22,000	16,685	17.5	12.20
1487	Limestone	Wyo.	4	30,000	27,750	20.5	12.60
1324	Limestone (gray)	Mo.	5	15,960	14,410	19.7	13.16
1560	Molybdenum ore	Colo.	10	29,050	19,970	19.4	14.09
1469	Trap rock	Mont.	3	20,800	18,923	24.0	14.70
1402	Limestone (coarse)	Mich.	4	19,100	16,785	27.0	14.75
1396	Shale	Penn.	7	9,100	8,106	22.1	15.06
1397	Iron ore	N. Y.	6	29,700	24,305	23.4	15.64
1578	Trap rock	Calif.	6	20,150	17,900	28.8	16.74
1571	Specular hematite	Mich.	6	38,600	33,070	29.8	17.03
1318	Limestone	Ark.	4	24,480	20,000	33.2	17.91
1318B	Limestone	Mo.	6	23,540	19,222	23.8	18.00
1456	Taconite	Minn.	5	48,600	41,560	36.6	19.88
1515	Iron ore	Minn.	9	62,400	38,550	40.0	25.29
1407	Dumortierite	Mich.	3	51,600	42,233	60.2	38.10

The mean highest value for all of the tests is 148 per cent of the mean average value.

Both compression and impact tests have been made on 22 different materials. These are tabulated in Table 5, the materials being listed in the order of increasing average impact strength.

Comparison with the observed resistance to crushing these materials in commercial installations indicates that the impact results may be closer to the resistance to crushing than the results of compression tests on inch cubes. This is especially notable in the case of dumortierite (test 1407), which is extremely resistant to crushing but whose compressive strength is not particularly high. However, more data must be collected before the relative merits of the two methods can be accurately evaluated.

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DISCUSSION

(*O. C. Ralston presiding*)

HARLOWE HARDINGE.*—Has the impact method described in the paper been used to compare the resistance to reduction in size of various materials with actual operation results of mills in the field?

Is this impact method a better index of the true resistance to grinding under actual field

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* President, Hardinge Company, Inc., York, Pennsylvania.

conditions than other methods the author has reported in the TRANSACTIONS?

F. C. BOND (author's reply).—The impact crushing device was designed to measure relative resistance to crushing, or what may be called the crushability, and is not used for comparing the resistance to grinding, or grindability. The correlation between crushability and grindability of different materials is not at all close, since fractures, zones of weakness, and structural features of rock have a much greater effect upon the crushability than upon the grindability. We still depend upon our standard grindability tests for measuring resistance to grinding, and use the impact crushing tests only in relation to crusher installations.

The impact crushing device has several advantages over the measurement of crushing strength in pounds per square inch as an index of crushing resistance.