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WEAR RESISTANCE OF NATURAL STONE FLOORING

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ABSTRACT

Since the hardness testing devices in general use are not well adapted to floor surfacing materials, an apparatus for this purpose was designed. In order to determine if the results of tests with this device bear a definite ratio to wear in service, a comparison was made with 22 materials which had been on stair treads under service conditions and which represented about 10 percent of the total number received for tests. The degree of correlation between the tests and actual wear was found to be high and, hence, the test values should enable one to predict service wear with a fair degree of accuracy. Subsequently samples representing the marbles, limestones, slates, etc., commonly used in floor surfaces were tested, and the approximate values for the different types range as follows: Marbles, from 7 to 42; limestones, 2 to 24; sandstones, 2 to 26; slates, 6 to 12; granites, 44 to 66; serpentines, 15 to 111; travertines, 5 to 17. On this scale the most resistant material (quartz) showed a value of 180. Materials used for general flooring purposes in this country show values between 15 and 20.

CONTENTS

I. INTRODUCTION

The purpose of this investigation was to determine the comparative resistance to wear of the natural stones commonly used in floor surfaces and other parts of buildings exposed to the abrasive action of traffic. For several years there has been a growing demand for information on this subject which could not be adequately supplied from published data on hardness tests. The United States Bureau of Public Roads [1] has published a large amount of valuable data on

[1] Bureau of Public Roads, Bulletins Nos. 44, 370, 1132; Dept. of Agriculture, Washington, D.C., Goldbeck, Jackson, Hubbard.

tests with the Dorry and Deval machines, but the materials referred to usually do not correspond with those used in floors. The rate of wear on heavy duty floors is of considerable importance and due consideration to wearing qualities in the selection of materials may often prevent annoyance or replacement. When floors are made a decorative feature of the building the design often requires the selection of materials for color effect. In the absence of comparative data on the wearing qualities of the different materials one may select an unfortunate combination that will soon result in an uneven surface.

The subject of accidents in public buildings has been a matter of some concern. While the question of slipperiness is not within the scope of this study, it seems probable that irregular surfaces, especially on stair treads, are a contributing factor to accidents. Some varieties of stone which have high decorative values due to their veined or mottled appearance may wear unevenly. Where a considerable range in wear resistance is shown for different specimens of a sample the material may be expected to wear unevenly in service.

An examination of the methods and apparatus employed for hardness determinations shows various conceptions of this property. These methods may be roughly classified as follows: the determination of the resistance of the material to (1) penetration of a spherical surface or conical point (Brinell [2] and Rockwell [2] tests); (2) scratching with materials of standard hardness (Moh's hardness scale [3]); (3) abrasion with loose, granular materials of standard hardness (Dorry [4] and Amsler [5] tests); (4) the cutting action of a hard granular substance of standard hardness under impact (sandblast); (5) a combination of impact and abrasion between broken fragments of the sample (Deval test [6]); (6) cutting with a tool of standard hardness (Bauer drill test [7] for metals and Jagger's boring test [8] for minerals).

The test for flooring materials should simulate closely the conditions to which a floor is exposed. Although the surface of a floor is evidently subjected to a mild form of impact, the greatest amount of wear is probably due to cutting or scratching of hard particles forced into or rolled over the surface under pressure. While the Deval test combines the two factors assumed to be largely concerned in the wear on floors, the impact action is much greater than the abrasive action. Besides, the type of floor samples usually received for test purposes are not well adapted to this apparatus. The Dorry and Amsler machines produce an abrasive action similar to that occurring on floors, but some modifications would be necessary to adapt them to the test samples. It was considered more feasible to design an apparatus of compact form and determine experimentally whether it produced results comparable to the wear on floors.

The results given in tables 1 to 8 inclusive were determined at low humidity (below 35) to afford a more definite comparison. Since the abrasive resistance of some materials decreases appreciably as the humidity increases, the test values may not properly rate all materials as to service wear when used under various conditions of humidity.

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[2] B. S. Jour. Research (RP185), vol. 5, p. 19, 1930, S. N. Petrenko.
[3] Textbooks on mineralogy such as Dana's and Idding's, Moses and Parsons, etc.
[4] U.S.Dept.Agri., Bu. of Public Roads Bull. No. 44, Albert T. Goldbeck & Frank H. Jackson.
[5] Herschwald's Handbuch der bautechnischen Gesteinprüfung Gebrüder Borntraeger, Berlin.
[6] See footnote 4.
[7] B. S. Tech. Paper No. 11, Ralph P. Devries.
[8] Am. Jour. Sci., vol. 4, p. 399, 1897, T. A. Jagger, Jr.

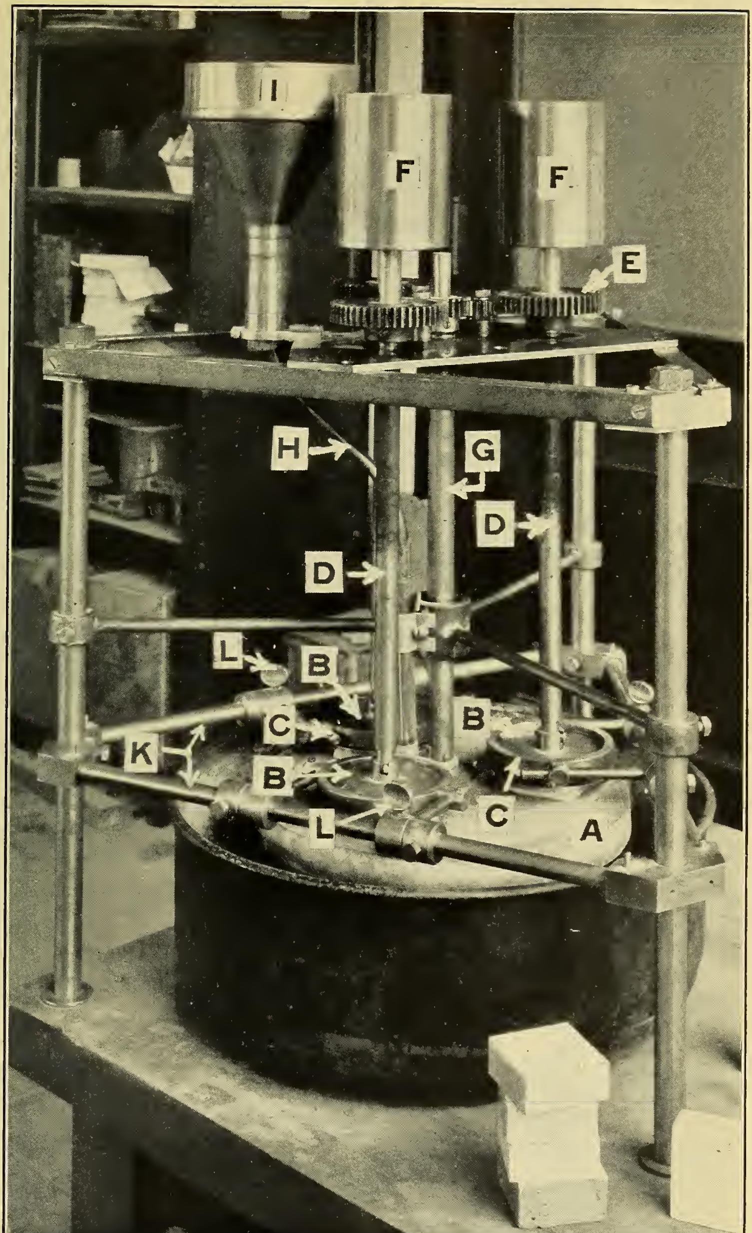

Figure 1.—*Photograph of apparatus with specimens in position for testing.*

A, Grinding lap; B, specimen holder; C, specimen holder guide rings; D, spinning rods; E, spinning gear; F, weight hoppers; G, spinning drive; H, abrasive conduit; I, abrasive hopper; K, guide ring support; L, guide ring clamp.

The samples tested were supplied by the producers as being representative of the various quarries or grades. Variations occur in all quarries and hence the test results can be only as representative as the samples were.

II. DEVELOPMENT OF APPARATUS AND TEST METHODS

1. LABORATORY TEST

(a) DESIGN OF APPARATUS

The original design of the testing apparatus was modified in some respects after the service tests (part II, 2) were made in order to secure a satisfactory agreement between the test values and service values. The final form is shown in figure 1.[9] It consists essentially of (1) a grinding disk 10 inches in diameter which is revolved in a horizontal plane at 45 r.p.m.; (2) a hopper for the abrasive and a conduit for feeding the abrasive to the disk; (3) a means of holding the specimens on the disk at a constant pressure; (4) a means of distributing fresh abrasive over the disk as the grinding proceeds. Three disk-shaped specimen holders having recesses 2 by 2 by ⅜ inch for the specimens are spaced at 120° angles around the disk. Guide rings hinged to the frame support the specimen holders near the grinding disk. The holders are weighted and revolved by means of vertical rods. The lower ends of the rods fit loosely in sockets in the tops of the specimen holders, the upper ends pass through bearings and are geared to the main drive shaft which extends upward through the grinding disk. On the upper end of each rod is a receptable for weights. The weight on each specimen includes the weight of the holder, the rod, one spur gear, the receptacle, and enough added weight to make 2,000 grams.[10] The usual size of specimens is 2 by 2 by 1 inch, but any thickness from ½ to 2 inches can be used. The abrasive (no. 60 artificial corundum) flows in the dry condition from an orifice 0.1 inch in diameter, which is ⅜ inch above the grinding disk and 1¼ inches from the center. A device is attached to each specimen holder for distributing fresh abrasive over the disk and moving the worn material outward over the edge as the test proceeds.

(b) TEST PROCEDURE

The specimens are weighed in the dry condition, placed in the apparatus, and subjected to abrasion for 5 minutes (225 revolutions of the grinding disk), after which they are weighed again. Before each succeeding test the disk is brushed free of the used grit and stone dust, after which a fresh layer of grit is distributed over the surface.

The difference between the original and final weights of the specimens is inversely proportional to their wear resistances. However, the most satisfactory means of comparing the resistance of materials of variable density is to use the volume losses rather than the weights.

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[9] A detail drawing of this apparatus may be found in vol. 28, 1928, part II, p. 855, Proc.A.S.T.M., D. W. Kessler.

[10] It was found to be more convenient to keep the superimposed weight constant and apply a correction for the specimen weight. The rate of abrasion was found to be proportional to the pressure; for example, with 4,000 grams load the abrasion was twice that for 2,000 grams load. The correction factor is

$$\frac{2{,}000}{W_s+2{,}000}$$

where W_s is the average weight of the specimen.

The volume is obtained by dividing the weight-loss [11] by the bulk density of the material. The bulk density, G is easily obtained by dividing the weight of the dry specimen, W_1, by $W_2 - W_3$ where W_2 equals the weight of the specimen after soaking in water for an hour or more and surface dried with a towel, and W_3 equals the weight of the saturated specimen suspended in water.

The abrasive resistance is expressed as $H_a = 10/V$ where V is the volume of abraded material and equals weight-loss/G. Incorporating the correction factor $\frac{W_s + 2{,}000}{2{,}000}$ for the weight of specimen, the formula becomes:

$$H_a = \frac{10(W_s + 2{,}000)G}{2{,}000 W_a} \tag{1}$$

where W_a is the weight in grams of material abraded in the test, and W_s is the mean of the original and final weights of the specimen. This form of equation has an advantage over the linear equation used for computing the results in the Dorry test because the hyperbolic form above gives positive values in all cases while the Dorry formula may give negative values for very soft materials. The H_a values stand in direct relation to the abrasive resistance and hence afford a simple means of comparison.

It was found by preliminary tests that variations in humidity affected the results quite appreciably for some materials. Tests on such materials at high humidities generally gave lower H_a values than when tested at low humidity. For this reason all of the tests were made when the relative humidity was 35 or lower.

2. SERVICE TESTS

Service values were obtained by subjecting a number of tiles to the action of foot traffic on a staircase. The tiles used in these experiments were 4 by 4 by ⅞ inches and 12 tiles were used on each step. A form was made for each tread, the form having wood sides, a composition-board bottom and a metal strip for the lip. These forms were held rigidly in place on the treads by means of bolts and the tiles were laid into the recess. In order to prevent abrasion of the tiles against each other or against the metal lip the recess was made about ⅛ inch oversize and thin strips of cardboard inserted between the tiles and also around the sides.

The 22 materials used in this experiment are listed in figure 2. Preliminary experiments showed that the wear was not uniform over the surface of one tread, the greatest amount being at the middle portion and near the front. There were 2 rows of tiles on each tread, 1 row of 6 occupying the portion next to the riser and the other row the portion to the front. In order to compare the amounts of wear on different materials it was necessary to have a standard of reference in all of the 12 positions, hence the middle step in the flight was covered entirely with marble no. 7. In order to check the assumption that the wear at any given position on different steps was uniform, two tiles of marble no. 7 were placed on each of the other treads.

[11] All weighings to the nearest 0.01 g.

After 6 weeks of exposure to service conditions the tiles were removed, cleaned, dried, and weighed for comparison with the original weights. The weight losses were reduced to volume losses as in the laboratory tests. The results indicated that the wear was fairly uniform for the same positions on different steps.

The wear ratios were computed between the standard marble and the other materials, only identical positions on each tread being compared. For instance, if the wear of the standard marble for one position was 0.25 cc, this figure and those obtained for all other materials in the same relative position on other steps were divided by 0.25. Thus the wear of the reference material was expressed as unity and the others in their appropriate ratios. Since the H_a values are reciprocals of wear, the service wear ratios also are expressed as reciprocals to afford a direct comparison.

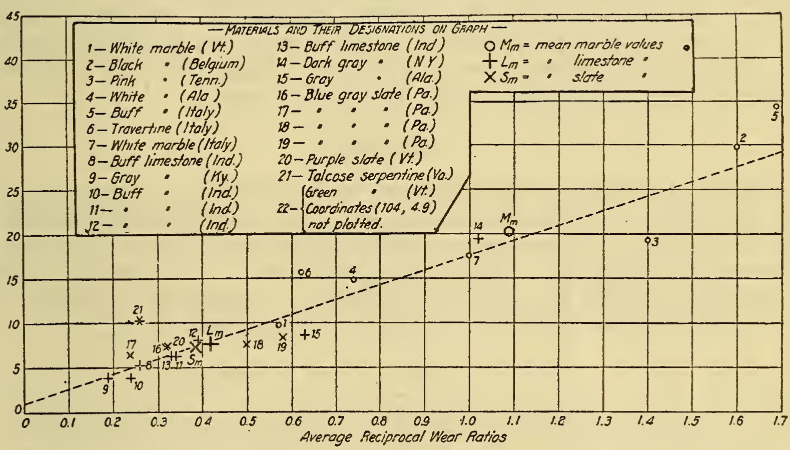

FIGURE 2.—*Relation between H_a values and average reciprocal wear ratios for 21 materials.*

3. CORRELATION OF PRELIMINARY LABORATORY VALUES WITH SERVICE WEAR

In figure 2 the H_a values are plotted against the wear ratio reciprocals for all materials subjected to the service test except the serpentine. The deviations from a linear relation are probably within the precision of the tests.

The correlation coefficient (r) was computed for the values of the two variables given in figure 2 by the formula

$$r = \frac{\Sigma(xy) - \dfrac{\Sigma(x)\Sigma(y)}{N}}{\sqrt{\left(\Sigma x^2 - \dfrac{(\Sigma x)^2}{N}\right)\left(\Sigma(y)^2 - \dfrac{(\Sigma y)^2}{N}\right)}} \tag{2}$$

where x and y are the variables and N is the number of determinations. This gave the value $r = 0.990$ indicating a high degree of correlation. The coefficient of alienation, $K = \sqrt{1 - r^2}$, gives a value of $K = 0.14$ which indicates that the error in estimating service values from H_a values will ordinarily be about one seventh of the error made by a random selection. Expressing the individual deviations from the linear relation as percentages of the measured service values it appears that the probable error of rating materials from their H_a values is 16.6 percent. These computations are based on the 22 samples used in the service tests and, since the samples cover practically the entire range in abrasive hardness of stone flooring, the correlation is assumed to apply to all the 215 materials tested.

III. RESULTS OF LABORATORY TESTS

The data obtained are given in tables nos. 1 to 8, inclusive. The samples are designated by serial numbers, grouped according to producing districts and briefly described as to class and color. Where more than one sample was tested from a given quarry in which the product was fairly uniform, the results are included under one serial number and the number of samples indicated in column 4. Where tests were made on two varieties of stone from one quarry, the results are given under different serial numbers. Each test was made on a different specimen except where otherwise noted.

1. MARBLE

Table 1 gives the results of tests on 78 marbles; 50 domestic and 28 imported. Of the 8 samples classed as dolomitic marbles, 3 (nos. 9, 52, and 58) are not true dolomites since they are too low in magnesium carbonate. Also 3 samples (nos. 11, 20, and 23) classed as calcites contain appreciable amounts of magnesium carbonate but not a sufficient amount to be classed as dolomites.

Table 1.—*Results of tests on marble*

[Note.—Column 5 gives the number of tests. Where "a" follows the number, 2 tests were made on 1 specimen; where "b" follows the number, 2 tests were made on each of 2 specimens]

Serial numbers of samples	Variety	Source	Number of samples	Number of tests	Abrasive hardness H_a		
					Maximum	Minimum	Average
1	Light bluish gray calcite	Vermont	1	4 b	14.6	13.3	13.8
2	Dark bluish gray calcite	do	1	4 b	12.8	11.7	12.3
3	Dark veined white calcite	do	2	7	14.3	9.5	10.8
4	Light-gray calcite	do	1	4 b	10.8	10.4	10.5
5	Dark bluish gray calcite	do	1	4 b	15.4	15.3	15.4
6	Bluish gray calcite	do	1	4 b	13.0	12.0	12.4
7	Light-gray calcite	do	1	4 b	14.2	13.6	13.9
8	White and green calcite	do	1	2	6.7	6.7	6.7
9	Red and white (dolomitic)	do	1	4 b	33.9	24.6	30.9
10	White calcite	do	2	9	9.1	7.6	8.4
11	Black calcite (fossiliferous)	do	1	4 b	26.0	22.9	24.8
12	Dark veined white calcite	do	1	1			12.0
13	do	do	1	5	12.1	10.5	11.2
14	do	do	1	3	14.8	9.0	13.5
15	Light bluish gray calcite	do	1	3	15.6	14.0	14.9
16	Green veined white calcite	do	1	3	10.8	10.0	10.3
17	White dolomite	New York	1	4 b	13.6	11.6	12.5
18	Pink fossiliferous calcite	do	1	4 b	17.1	15.3	16.6
19	Gray fossiliferous calcite	do	1	3	18.6	18.2	18.3
20	Gray calcite	do	1	4 b	15.4	13.5	14.6
21	White dolomite	Massachusetts	1	4 b	13.2	12.8	13.0
22	Buff dolomite	Maryland	1	3	13.4	12.1	12.9
23	Black calcite	Virginia	1	7	43.5	38.9	41.7
24	Pink calcite	Tennessee	1	4 b	21.9	18.9	20.2
25	Chocolate colored calcite	do	1	4 b	18.8	17.8	18.4

TABLE 1.—*Results of tests on marble*—Continued

Serial numbers of samples	Variety	Source	Number of samples	Number of tests	Abrasive hardness H_a		
					Maximum	Minimum	Average
26	Gray calcite	Tennessee	1	4 b	19.0	17.8	18.4
27	Pink calcite	do	1	4 b	19.5	18.7	19.2
28	Gray calcite	do	1	3	21.3	21.0	21.2
29	Pink calcite	do	1	2 a	20.3	19.2	19.8
30	Blue calcite	North Carolina	1	3	17.4	16.8	17.0
31	Blue and gray calcite	do	1	4 b	25.7	24.0	24.7
32	White dolomite	do	1	3	18.5	17.5	18.0
33	White and black calcite	Georgia	1	5	15.4	12.3	13.7
34	Light-gray calcite	do	1	3	12.6	11.5	12.2
35	Dark veined white calcite	do	1	3	11.7	10.9	11.3
36	Pink calcite	do	1	4 b	17.5	15.6	16.4
37	Dark veined white calcite	Alabama	1	4 b	17.3	12.5	15.0
38	Light-buff calcite	do	1	3	8.9	8.3	8.7
39	Gray calcite	do	1	3	16.2	14.4	15.4
40	Yellow veined gray calcite	Missouri	1	4 b	18.8	17.2	18.0
41	Pink calcite	do	1	4	19.3	16.9	18.0
42	Gray calcite	do	1	3	14.3	13.5	13.8
43	do	do	2	6	14.3	13.8	14.0
44	do	do	1	3	20.2	19.1	19.7
45	do	do	2	6	14.9	12.1	13.8
46	do	Arkansas	3	10	21.0	12.1	16.0
47	White calcite	Colorado	1	4 b	7.8	7.5	7.6
48	Gray calcite (fossiliferous)	Utah	1	6	33.4	28.7	31.1
49	Dark-veined white dolomite	California	1	3	15.5	14.0	14.9
50	Black and white calcite	Alaska	1	3	14.9	13.3	14.1
51	Black calcite	Belgium	1	4 b	33.5	27.7	30.9
52	White and pink (dolomitic)	Norway	1	3	15.3	10.2	13.3
53	Buff fossiliferous calcite	France	1	4	16.2	13.5	14.6
54	Violet pink calcite	do	1	4	28.2	20.7	24.2
55	Light pink calcite	do	1	4	35.2	29.0	32.6
56	Dark-veined red calcite	do	1	4	25.9	25.4	25.6
57	Pinkish buff calcite	do	1	4	35.6	33.8	35.0
58	Black and white dolomite	do	1	4 b	33.1	29.0	30.6
59	Buff calcite	do	1	3	31.2	30.8	31.0
60	Light buff calcite	do	1	3	15.2	14.9	15.0
61	do	do	1	4	30.9	29.6	30.3
62	Dark-veined white calcite	Italy	2	6	14.1	11.0	12.6
63	Buff calcite (fossiliferous)	do	1	3	34.4	32.9	33.7
64	Pink calcite (fossiliferous)	do	1	3	33.4	27.1	31.2
65	Gray calcite (fossiliferous)	do	1	3	34.0	33.7	33.8
66	White calcite	do	1	2	12.7	12.2	12.4
67	Dark-veined white calcite	do	2	6	16.5	13.4	14.8
68	do	do	1	4 b	14.5	13.8	14.2
69	Yellow-veined black calcite	do	1	4 b	25.7	23.5	24.5
70	Brown calcite	do	1	4	11.4	9.4	10.6
71	Light buff calcite	do	1	4	28.8	25.0	26.7
72	Black and yellow breccia (calcite)	do	1	4	27.0	23.8	25.8
73	Dark gray calcite (fossiliferous)	do	1	3	27.0	24.3	25.5
74	Light buff calcite	do	1	4 b	31.5	29.5	30.1
75	Violet gray calcite (fossiliferous)	Germany	1	4	26.4	25.0	25.6
76	Red calcite (fossiliferous)	do	1	3	22.5	20.4	21.4
77	Red and pink calcite	do	1	3	26.7	24.2	25.7
78	Yellow calcite	Algeria	1	6	25.6	17.3	21.2

The results do not indicate that the dolomites are more resistant to abrasion than the calcites, although mineralogists assign a higher hardness value to dolomite than calcite. It appears from the tests that the abrasive resistance is influenced more by the compactness of the material than by differences in hardness of constituent minerals. The highest H_a value obtained on dolomitic marble was 30.9 (no. 9) and the lowest 12.5 (no. 17). The highest value for any calcitic marble was 41.7 (no. 23) and the lowest 6.7 (no. 8).

2. LIMESTONE

Table 2 gives the results for 39 limestones, 34 domestic and 5 imported. The range in H_a values for the samples was from 24.1 to 1.3, with a weighted average of 8.4. This group consists of limestones used mainly for ashlar purposes although many of them are used in floors and steps.

TABLE 2.—*Results of tests on limestone*

Serial numbers of samples	Variety	Source	Number of samples	Number of tests	Abrasive hardness H_a		
					Maximum	Minimum	Average
1	Dark gray (crystalline)	New York	1	3	19.6	18.5	19.2
2	Statuary buff (oolitic)	Indiana	1	3	6.8	6.4	6.6
3	Select buff (oolitic)	do	1	5	6.7	5.0	6.1
4	do	do	1	3	7.1	6.6	6.9
5	Select gray (oolitic)	do	1	6	11.6	7.3	9.0
6	Hard buff (oolitic)	do	1	3	6.3	6.1	6.2
7	Rustic buff (oolitic)	do	1	3	5.7	5.0	5.4
8	Standard buff (oolitic)	do	1	3	6.6	6.4	6.5
9	do	do	1	2	5.1	5.1	5.1
10	Rustic buff (oolitic)	do	1	3	4.7	4.6	4.6
11	do	do	1	3	5.7	4.1	4.8
12	Select gray (oolitic)	do	1	3	8.4	7.9	8.1
13	Hard gray (oolitic)	do	1	3	18.3	14.8	16.9
14	do	do	1	3	6.4	6.2	6.3
15	Select buff (oolitic)	do	1	2	6.2	6.2	6.2
16	Standard buff (oolitic)	do	1	2	6.7	6.3	6.5
17	Gray (crystalline)	do	1	3	24.9	22.9	24.1
18	Gray (dolomitic)	Illinois	1	3	15.5	13.9	14.9
19	Gray (oolitic)	Kentucky	2	9	5.6	4.5	4.9
20	do	Alabama	4	14	9.7	4.9	6.9
21	Light buff (earthy)	Florida	3	9	3.1	1.5	2.1
22	Pink (dolomitic)	Minnesota	2	6	12.0	10.2	11.0
23	Yellow (dolomitic)	do	2	6	13.1	10.0	11.2
24	Buff (dolomitic)	do	2	6	12.2	8.3	10.0
25	Gray (dolomitic)	do	1	3	10.2	9.8	9.9
26	Bluish gray (dolomitic)	do	1	3	9.2	7.7	8.6
27	Buff (dolomitic)	do	1	3	11.2	9.2	10.3
28	Light gray (dolomitic)	do	1	3	7.6	7.1	7.3
29	Veined buff (dolomitic)	do	1	3	8.5	7.7	8.2
30	Buff (oolitic)	Kansas	1	3	3.7	3.5	3.6
31	Gray (oolitic)	Oklahoma	1	6	8.0	7.2	7.6
32	Buff (semicrystalline)	Texas	1	3	7.8	6.6	7.1
33	Gray (semicrystalline)	do	1	6	5.1	4.6	4.8
34	Light gray (oolitic)	do	1	3	1.8	1.0	1.3
35	Light buff	France	1	4	17.6	12.3	14.6
36	Buff	do	1	4	16.0	11.4	14.0
37	Light buff (semicrystalline)	do	1	4	7.3	4.5	7.2
38	Buff (oolitic)	do	1	4	6.4	4.2	5.2
39	Pink (fossiliferous)	Italy	1	5	9.0	7.6	8.4

3. SANDSTONE

Results for 22 sandstones are given in table 3. The range is about the same as for the limestones. Those used mainly for ashlar purposes (nos. 13, 14, and 15) generally show rather low H_a values. This brings out clearly the fact that abrasive resistance depends to a large extent on the cohesiveness of the stone. A test on a specimen cut from a quartz crystal gave an H_a value of 180. No doubt the individual sand grains in sandstone are as hard as the value given for quartz, but abrasion of the sandstone results in loosening and removing the grains. Modulus of rupture determinations were made on several of these sandstones in connection with other investigations, and the relation between this property and abrasive hardness is discussed in part IV.

TABLE 3.—*Results of tests on sandstone*

Serial numbers of samples	Variety	Source	Number of samples	Number of tests	Abrasive hardness H_a		
					Maximum	Minimum	Average
1	Brownstone	Massachusetts	1	2	10.8	10.8	10.8
2	Bluestone	New York	5	21	18.9	10.4	13.5
3	Purple flagstone	New Jersey	1	4	20.1	9.7	14.3
4	Blue flagstone	do	1	5	20.7	15.1	18.8
5	Gray flagstone	do	1	5	18.5	11.7	14.7
6	Brown flagstone	do	1	5	17.6	12.6	15.5
7	Gray sandstone	Pennsylvania	1	5	11.3	8.9	10.1
8	Buff flagstone	do	1	5	25.5	19.0	23.3
9	Blue flagstone	do	1	4	29.8	19.2	26.4
10	Red flagstone	do	1	5	17.2	13.8	15.6
11	Blue flagstone	do	1	3	15.0	12.2	14.0
12	Bluestone	do	1	3	23.2	13.1	18.2
13	Gray sandstone	Ohio	1	3	5.2	4.9	5.1
14	Buff sandstone	do	1	3	4.3	4.0	4.2
15	do	do	1	3	1.8	1.4	1.6
16	Bluish gray (fine grained)	do	5	19	8.8	5.2	6.3
17	Buff (fine grained)	do	1	5	4.5	3.7	4.0
18	Bluish gray (fine grained)	do	4	22	9.2	6.0	7.3
19	Free stone (fine grained)	Kentucky	2	13	12.0	7.2	9.0
20	Buff flagstone	Tennessee	6	24	46.0	9.6	29.0
21	Gray (fine grained)	do	1	3	20.4	14.7	17.7
22	Buff (coarse grained)	California	1	3	15.5	11.0	12.9

4. SLATE

Table 4 gives results for 32 domestic slates. The greatest use of slate is for roofing purposes where abrasive qualitites are not important, but some of the Pennsylvania and Vermont slates are used in stair treads and flooring. The tests of different slates show considerable uniformity in the abrasive resistance. The highest mean H_a value for any sample was 11.7 (no. 13) and the lowest 5.6 (nos. 27 and 29) with a weighted average for all of 7.7.

TABLE 4.—*Results of tests on slate*

[NOTE.—Column 5 gives the number of tests. Where "a" follows the number, 2 tests were made on each of 3 specimens; where "b" follows the number, tests were repeated on 2 of the 3 specimens; where "c" follows the number, 3 tests were made on each of 3 specimens]

Serial numbers of samples	Variety	Source	Number of samples	Number of tests	Abrasive hardness H_a		
					Maximum	Minimum	Average
1	Purple	Vermont	1	5 b	9.0	6.9	8.3
2	Unfading green	do	1	6 a	8.1	7.0	7.6
3	Green and purple	do	1	5 b	8.5	7.6	8.0
4	Weathering gray	do	1	5 b	7.9	7.5	7.7
5	Unfading purple	do	1	5 b	7.3	6.7	7.1
6	do	do	1	6 a	9.2	8.8	9.0
7	Unfading green	do	3	14	12.0	8.1	9.6
8	Green and purple	do	1	4	8.9	7.4	7.9
9	Dark gray	Maine	2	6	9.8	8.8	9.4
10	Red	New York	1	6 a	12.2	10.7	11.4
11	Silver gray	do	1	5 b	7.8	7.3	7.5
12	Gray and black	do	1	5 b	7.2	7.0	7.1
13	Purple and green	do	1	6 a	15.2	7.4	11.7
14	Weathering green	do	1	5 b	8.0	7.6	7.7
15	Unfading green	do	1	6 a	7.6	7.2	7.5
16	Blue-gray, clear	Pennsylvania	2	6	7.0	5.8	6.3
17	do	do	1	3	7.7	7.5	7.6
18	do	do	1	3	6.6	6.3	6.5
19	do	do	1	5 b	7.2	6.3	6.5
20	do	do	5	15	7.2	6.2	6.9
21	Blue-gray, ribbon	do	1	3	7.8	7.4	7.5
22	Blue-gray, clear	do	1	3	7.7	7.0	7.4
23	do	do	7	29	7.7	5.8	6.5
24	Blue-gray, ribbon	do	2	15	7.2	6.2	6.6
25	Blue-gray, clear	do	4	12	6.4	5.6	6.0
26	Blue-gray, ribbon	do	2	6	7.2	6.5	6.9
27	Blue-gray, clear	do	2	6	5.8	5.5	5.6
28	Hard vein	do	1	9 c	9.3	6.8	8.2
29	Dark gray	Maryland	1	3	5.7	5.5	5.6
30	do	Virginia	1	5 b	12.2	9.9	10.9
31	Green	Georgia	1	5 b	8.9	7.9	8.5
32	do	Tennessee	1	6 a	7.0	6.5	6.8

5. GRANITE

Table 5 gives results of tests on 11 domestic granites. All show high values and a lower percentage variation from the mean than any of the other types of stone. The minerals in these granites are mainly quartz and feldspar. The H_a values obtained are usually between those obtained by testing specimens cut from crystals of the two minerals but are much nearer the feldspar values. Granites usually possess a high cohesive strength but apparently the wear test produces a slight crumbling effect as noted for the sandstones. Repeated tests on samples of polished granite showed higher H_a values as the depth of abrasion was increased. This seems to substantiate the theory that hard stones are injured to some extent near the surface by the finishing process.

TABLE 5.—*Results of tests on granite*

[Note.—Column 5 gives the number of tests. Where "a" follows the number, 2 tests were made on each of 3 specimens; where "b" follows the number, 3 tests were made on each of 3 specimens]

Serial numbers of samples	Variety	Source	Number of samples	Number of tests	Abrasive hardness H_a		
					Maximum	Minimum	Average
1	Pink biotite granite	Maine	1	3	69.2	60.2	63.2
2	Light gray muscovite—biotite	do	1	3	48.5	40.8	45.9
3	Bluish-gray muscovite—biotite	New Hampshire	1	3	72.5	56.6	64.0
4	Pink biotite granite	do	1	3	72.9	60.2	66.4
5	Green biotite—hornblend	do	1	3	75.1	60.6	66.3
6	Light gray quartz—monzonite	Vermont	1	3	55.0	37.0	43.9
7	Gray biotite granite	do	1	3	55.7	50.0	53.2
8	Gray hornblend granite	Massachusetts	1	3	76.0	59.0	67.7
9	Green hornblend granite	do	1	6 a	98.4	77.3	87.9
10	Gray biotite granite	North Carolina	1	3	53.9	44.6	50.5
11	Dark gray hornblend	Colorado	1	9 b	65.2	42.9	59.5

6. SERPENTINES

The results in table 6 for 5 domestic and 6 imported serpentines show a large variation and some values higher than any obtained for granite.

TABLE 6.—*Results of tests on serpentine*

[NOTE.—Column 5 gives the number of tests. Where "a" follows the number 2 tests were made on each of 2 specimens]

Serial numbers of samples	Variety	Source	Number of samples	Number of tests	Abrasive hardness H_a		
					Maximum	Minimum	Average
1	Green, pale green veins	Vermont	1	3	97.6	86.1	92.6
2	Dark green, pale green clouds	Massachusetts	1	5	16.7	12.9	15.0
3	Pale green	New Jersey	1	4	40.6	30.2	35.3
4	Dark green, pale green veins	Maryland	1	6	158.0	75.0	111.4
5	Green to grayish-green	Georgia	1	4 a	26.9	23.0	24.9
6	Pale green and gray	Sweden	1	6	22.7	15.6	18.8
7	Emerald-green	Italy	1	4	37.6	31.7	34.8
8	Green, white veins	do	1	3	81.0	65.0	74.2
9	Red, white, and green	do	1	4 a	21.0	16.0	17.8
10	Dark green, white veins	France	1	4	15.3	10.2	13.3
11	Green, white veins	Greece	1	4 a	80.0	74.3	77.2

Textbooks on mineralogy give the hardness (Moh's scale) of the mineral serpentine as ranging from 2.5 to 4.0 while the principal granite minerals, quartz, and feldspar, are 6 and 7, respectively. The high values obtained for some of the serpentines would be surprising but for the fact that this type of material is seldom if ever pure serpentine. Such hard minerals as pyrite, hornblend, olivine, and pyroxene are usually present in variable amounts.

7. TRAVERTINES

Table 7 gives the results of tests on 7 domestic and 4 imported products. Some of these are travertines in a commercial sense only. This is especially true of the black travertine (no. 11) which is an igneous rock. Also the fossiliferous and sedimentary limestones (nos. 1, 2, 3, and 9) are not travertines according to a strict interpretation of the term, but are known in the trade as such on account of their cellular structure.

TABLE 7.—*Results of tests on travertine*

[NOTE.—Column 5 gives the number of tests. Where "a" follows the number, 2 tests were made on each of 2 specimens]

Serial numbers of samples	Variety	Source	Number of samples	Number of tests	Abrasive hardness H_a		
					Maximum	Minimum	Average
1	Buff (sedimentary)	Florida	5	20	17.6	5.6	12.4
2	Buff (fossiliferous)	Georgia	1	4 a	13.4	11.7	12.6
3	Buff (sedimentary)	Minnesota	1	3	12.5	10.0	11.2
4	Buff	Montana	1	3	14.4	14.1	14.3
5	Pink	do	1	3	13.3	8.8	11.4
6	Gray	do	1	3	5.8	5.0	5.4
7	Pinkish-buff	Colorado	1	3	8.8	8.3	8.6
8	Buff	Italy	1	3	16.7	15.2	15.7
9	Light buff (sedimentary)	France	1	2	.6	.6	.6
10	Buff	Germany	1	4	18.4	15.3	16.5
11	Black (vesicular basalt)	do	1	4	50.7	35.6	40.6

8. MISCELLANEOUS MATERIALS

Certain grades of the secondary rocks classed as talcose serpentine and chloritic amphibole (nos. 1, 2, 6, 7, and 8) are used to a considerable extent in floors and stair treads. The results on these are given in table 8 with results on 3 common minerals for comparative purposes. The large variations in the secondary rocks from different quarries (nos. 1 to 6, inclusive) or different ledges (nos. 7 and 8) are due evidently to the amount of alteration from the original igneous rock. In general, the softer varieties of these materials are used in tanks, tubs, table tops, etc., where the abrasive factor is not important.

TABLE 8.—*Results of tests on miscellaneous materials*

[NOTE.—Column 5 gives the number of tests. Where "a" follows the number, 5 tests were made on 2 specimens; where "b" follows the number, 3 tests were made on 1 specimen]

Serial numbers of samples	Variety	Source	Number of samples	Number of tests	Abrasive hardness H_a		
					Maximum	Minimum	Average
1	Talcose serpentine	Virginia	1	2	23.2	22.0	22.6
2	do	do	1	2	10.0	9.6	9.8
3	do	do	1	2	5.6	5.4	5.5
4	do	do	1	2	4.9	4.2	4.6
5	do	do	1	2	4.4	4.2	4.3
6	do	do	7	14	21.6	11.7	16.3
7	Chloritic amphibole	do	1	3	16.2	15.7	16.0
8	do	do	3	11	9.9	5.6	7.2
9	Feldspar (orthoclase)	New York	1	3	55.0	50.5	52.7
10	Feldspar (albite)	?	1	5 a	89.8	75.0	80.9
11	Quartz	Brazil	1	3 b	187.0	176.0	179.7

IV. DISCUSSION OF RESULTS

The wear resistance values obtained by this test procedure and the commonly accepted Moh's scale values for some materials are apparently not in accord. This may be due to the different forms in which minerals occur. The mineralogist deals usually with individual crystals of the substance while rocks are mainly aggregations of small crystals. Loosely bonded aggregations of hard minerals in this test invariably show low resistance to wear. This is illustrated by the tests on some of the sandstones which were almost entirely quartz but gave lower H_a values than most of the limestones. The abrasive resistance of sandstone seems to depend mainly on its cohesive strength. The correlation coefficient (r) between the H_a values and modulus of rupture values for 21 sandstones, computed by formula (2), was 0.81.

Accuracy and dependability of test methods are essential considerations. There is no standard process for determining the accuracy of an abrasive hardness test. If it were possible to secure an absolutely homogeneous material, repeated tests would show the variations in the test itself. However, the selection of a material to be used for a standard must depend on some measurement of uniformity in abrasive resistance which again involves the errors of the test employed. A considerable number of the materials tested in this investigation gave quite uniform results for the different determinations made on them. Probably the best way of studying the accuracy of the test is to consider the variations obtained from a large number of determinations on materials which appear to be homogeneous. The range in values obtained for any particular material may represent either the sums or differences of variations in the material and inaccuracies of the test, but the mean variation for a large series of tests will tend to balance these variable effects.

A study was made of the variations obtained on 85 samples of the 78 marbles by expressing the difference between the highest and lowest values obtained on each sample as a percentage of the mean of all determinations on that sample. The mean of all the percentage variations for the 85 samples was found to be 11.3 percent. For 66 of these samples, which appeared to be fairly uniform in composition and texture, the mean percentage variation was 9.2 percent. Forty-two samples of slate gave a percentage variation of nearly 11 percent, but when those which were obviously nonhomogeneous were eliminated from the computations, the mean percentage variation was found to be less than 8 percent. Such considerations seem to indicate that the precision of the test is within ±5 percent.

Experience with various floor-surfacing materials has shown the need for adapting the wearing surface to traffic conditions. Entrance ways to public buildings usually require paving materials of high wear resistance. Hallways, stair treads, and other places of concentrated traffic also need some degree of care in the selection of the surfacing materials, while for spaces having a good distribution of traffic the selection is not so important.

A comparison of the actual service wear of widely used stones with their H_a values gives fairly definite information as to what test values should be specified for any particular case where the traffic conditions can be estimated. An interesting comparison between two marbles used in the floor of an important railroad station may be cited. A red marble giving an H_a value of approximately 31 was used with a white marble giving a test value of about 10. After nearly 30 years of service this floor has worn to a very uneven surface in which the red tile surfaces are standing quite perceptibly higher than those of the white tiles. This particular case has brought forth considerable comment and was, to some extent, instrumental in bringing about this investigation. Observations on several of the more important flooring marbles under various conditions of service seem to justify the following statements: Surfacing materials showing H_a values of 30 or higher are very resistant to wear and should prove reasonably satisfactory under severe traffic conditions. For railroad stations, hotel lobbies, department stores, etc., the surfacing materials should test as high as 15 or, in some cases, 20. For a large percentage of floor areas where the traffic conditions are not especially severe good service may be obtained from surfacing materials testing as low as 6.

V. CONCLUSIONS

1. The correlation existing between the results obtained with the testing apparatus and the results of service tests seems to be such as to enable one to satisfactorily predict service wear from the abrasive resistance (expressed as H_a) values.

2. The abrasive resistance of stone depends on its cohesive strength and the hardness of the minerals of which it is composed.

3. Determinations on 78 marbles including both calcites and dolomites show that some varieties are five or six times as resistant to abrasion as others. The results do not indicate that dolomitic marbles are more resistant than calcitic marbles.

4. As a class the limestones are shown to be considerably less resistant to abrasion than the marbles although those limestones which approach marble in density and strength usually show resistance values comparable to those of marble.

5. The abrasive resistance of sandstone depends on the cohesion between the sand grains. The varieties used for flagging gave values similar to those of the marbles, while those used mainly for ashlar purposes gave low resistance values.

6. The slates studied gave quite uniform test results with an average somewhat lower than the average for limestone.

7. The granites give relatively high test results in a rather narrow range for the 11 samples tested. Duplicate tests on polished specimens showed higher values with increasing depth which seems to indicate that this material is injured appreciably near the surface by the finishing process.

8. The materials grouped under the trade classification of travertines gave variable results. Those samples which could be classed as real travertine gave values somewhat below the average for marble.

9. The average value for the serpentines was somewhat below the average for granite but the range of values for the serpentines was very large and two samples gave values much higher than any of the granites.

10. Materials which are formed from igneous rocks by surface weathering, such as serpentines and chloritic amphiboles, show wide variations in resistance to abrasion, depending on the degree of weathering.

11. Since the values for most of the types of stone tested overlap in many instances, it is not possible to evaluate the relative wear resistance of materials by type alone.

Washington, August 30, 1933.