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BUILDING MATERIALS AND STRUCTURES

REPORT BMS98

Physical Properties of Terrazzo Aggregates

by

DANIEL W. KESSLER
ARTHUR HOCKMAN
and ROSS E. ANDERSON

NATIONAL
BUREAU OF STANDARDS

BUILDING MATERIALS AND STRUCTURES REPORTS

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BUILDING MATERIALS *and* STRUCTURES

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by

DANIEL W. KESSLER, ARTHUR HOCKMAN, *and* ROSS E. ANDERSON

ISSUED MAY 20, 1943

The National Bureau of Standards is a fact-finding organization; it does not "approve" any particular material or method of construction. The technical findings in this series of reports are to be construed accordingly

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Foreword

The extensive use of terrazzo in a wide variety of buildings and some variability in its performance have caused a demand for more specific information on the materials used in making this product. Samples supplied for this investigation were secured from practically all of the domestic sources, and the producers are responsible for the selection of samples that are representative of the various aggregates. Since a few of these aggregates have been reported to give trouble in terrazzo mixtures, certain studies were made on these to determine if they contribute to excessive shrinkage in terrazzo mixtures. The laboratory studies reported herein were made to supply data on the aggregates that may be useful in controlling the quality of terrazzo and adapting it to various service conditions.

LYMAN J. BRIGGS, *Director.*

Physical Properties of Terrazzo Aggregates

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CONTENTS

ABSTRACT

Terrazzo specifications seldom afford adequate control over the quality of the aggregates, and since troubles sometime occur that are attributed to faulty aggregates, this investigation was undertaken to supply data on certain properties of the marbles used for making terrazzo chips. Comparative data are given on 77 samples of the commonly used products. Samples were supplied by 24 producers representative of various quarries in 12 States. The abrasive resistance, bulk specific gravity, absorption, and toughness tests were made on the rock in the original condition, and the percentage of dust, percentage of voids, and thickness grading tests were made on samples of No. 2 chips. Moisture-expansion tests were made on a few samples, including two thought to be faulty. Thermal coefficients were determined for one sample in three directions at right angles to each other.

A few samples were found to be rather low in abrasive resistance and friable enough to produce a considerable amount of dust in their shipping containers. Bulk specific gravity and absorption values varied considerably for the entire series and also for samples of similar mineral compositions.

The percentages of voids in chips of No. 2 aggregates were determined for samples when poured into a volumetric measure and also when compacted by vibrating. The void space obtained for loose chips is assumed to be comparable to that of portions measured by workmen in mixing, whereas the values for the vibrated samples give an indication of the minimum amount of cement paste required in a well-rolled terrazzo floor.

Since it is commonly believed that flat or thin chips are undesirable, a test was devised to separate samples of No. 2 aggregates (chips passing ⅜ in. and retained on ¼-in. mesh) into four thicknesses. The percentages of particles in each of these fractions show characteristic differences for samples that are similar in other properties. The shape of the particles seems to bear no relation to the type of crushing equipment used, but is a characteristic of the rock. A few terrazzo slabs were made with chips of unusual thickness distribution and were cut through the middle for studying the orientation of flat or elongated chips in the finished product. These show a tendency for such particles to assume horizontal positions when the terrazzo mixture is rolled, and thus interfere with the removal of excess cement paste.

One sample showed a large expansion while absorbing water, the amount being about equal to that of a 70° C temperature change, but the expansions for other samples were comparatively low. Contractions of the samples while drying were about the same as expansions while soaking. Thermal-expansion measurements on an impure calcite marble over the range −24° to +60° C gave variable coefficients over different temperature intervals, and for different directions in the stone. The highest coefficient (0.0000087) was obtained when the specimen was cooled from 60° to 0° C.

I. INTRODUCTION

Terrazzo floors are usually made with 1 part of portland cement and 2 parts of crushed marble (usually by volume), the aggregate sizes varying from ⅛ to ½ in. The colors are obtained by selecting aggregates of the desired hue and sometimes by adding a pigment to the mixture. Grinding the surface to expose the aggregate brings out the aggregate colors. The color scheme in any installation limits the number of aggregates from which the choice can be made, particularly if certain shades of red, yellow, and green are wanted.

In recent years, specification writers have shown a desire to place certain quality requirements on terrazzo aggregates, especially on the abrasive resistance. Since little information was available on many of the marbles used for terrazzo aggregates, this study was undertaken mainly to supply basic data for quality control. Incidentally, some attention was given to determining the causes of failure in a few cases where monolithic floors have cracked excessively.

Through the cooperation of the National Terrazzo and Mosaic Association and the aggregate producers, a representative collection of samples was obtained and tested to secure comparative data. The samples consisted of solid blocks of stone in its original state and also parcels of No. 2 aggregate (chips passing ⅜-in. and retained on ¼-in. openings). Each sample was selected by the producer to represent the average quality of a particular grade or variety of his product. Since most deposits of stone vary appreciably in different ledges or parts of one ledge, it should not be expected that the test results reported herein for particular products will conform exactly with those of materials of the same designations supplied in future years.

II. DESCRIPTION OF AGGREGATES

The chief characteristics of the materials and the methods used by producers in preparing the aggregates are briefly described in table 1. For most samples it was necessary to determine the classification, texture, structure, and color from the samples submitted, because examinations of the quarries were not feasible. Geological reports on the deposits were consulted whenever available, because such features as texture and structure are not always well defined in small samples. Details of the methods used in selecting the descriptive terms are outlined in the following sections.

TABLE 1.—*Description of raw materials and fabrication processes*

Sample number	Source and description of raw materials						Equipment used for crushing and grading	
	Source	Classification	Color		Texture	Structure	Type of crushers	Types of sieve openings
			Producer's designation	ISCC-NBS [1] designation				
1	Gantt's Quarry, Ala.	Calcite	White	White	Fine	Stratified	Gyratory	Square.
2	Canon City, Colo	Dolomitic	Red	Dusky red [2]	do	Massive [15]	Jaw; hammer mill	Do.
3	do	do	Yellow	Moderate yellow	do	do [16]	do	Do.
4	do	Calcite	Red	Weak purplish red	do	Stratified	do	Do.
5	do	do		Weak orange pink	do	do [17]	do	Do.
6	do	Dolomitic	Blue	Medium gray [3]	do	Massive [18]	do	Do.
7	do	do	Yellow	Weak yellow	do	Stratified [18]	do	Do.
8	do	do		Pale reddish brown.	do	do	do	Do.
9	do	Carbonaceous calcite.	Black	Dark gray	do	do [18]	do	Do.
10	do	Dolomitic	Cream	Weak purplish pink.	do	do [19]	do	Do.
11	do	Calcite	Pink	Pale red [4]	do	do [16]	do	Do.
12	do	do	Green	Light olive gray	do	do [18]	do	Do.
13	do	do	Yellow	Light brownish gray.	do	do [16]	do	Do.

See footnotes at end of table.

TABLE 1.—*Description of raw materials and fabrication processes*—Continued

Sample number	Source and description of raw materials						Equipment used for crushing and grading	
	Source	Classification	Color		Texture	Structure	Type of crushers	Types of sieve openings
			Producer's designation	ISCC–NBS [1] designation				
14	Whitestone, Ga	Talcose dolomite.	White	Light gray	Fine	Laminated	Gyratory; rotary crusher.	Square.
15	do	do	do	do	do	do	Hammer mill	Do.
16	Cardiff, Md	Serpentine	Green	Dusky green [5]		Veined	Jaw; gyratory crusher; rolls.	Round and square.
17	do	do	Light green	Weak green		do	do	Do.
18	Ashley Falls, Mass.	Dolomite	White	White	Medium	Massive	Jaw; rotary; rolls	Square.
19	West Stockridge, Mass.	Calcite	do		do	Veined	Gyratory; roll mill	Do.
20	Winona, Minn	Dolomitic		Weak yellow	Fine	Stratified [17]	Gyratory; jaw; rotary.	Round.
21	do	do		Pale brown	do	do [17]	do	Do.
22	Carthage, Mo	Calcite		Medium gray	Coarse	do	Gyratory; jaw	Square.
23	do	do		Light gray	do	do	Gyratory	Square and oblong.
24	Herculaneum, Mo	do		Yellowish gray	Fine	Massive [19]	Jaw; hammer mill	Round.
25	do	do	Pink	Weak orange pink	do	do	do	Do.
26	do	do	Buff	Yellowish gray	do	Stratified	do	Do.
27	do	do		do	do	do [19]	do	Do.
28	do	do		Pale brown [6]	do	do [20]	do	Do.
29	Sainte Genevieve, Mo.	do	Cream	Very pale orange	Coarse	Massive	Ring	Square.
30	Easton, Pa	Serpentine	Green	Weak yellow green.		do	Jaw; roller	Round.
31	Williams, Pa	Dolomitic		Light yellowish brown.	Fine	Stratified	Jaw; gyratory	Square.
32	Nottingham, Pa	Serpentine	Light green	Very dusky green		Veined	Jaw; roller	Round.
33	do	do	Dark green	do		do	do	Do.
34	Ashbury, Tenn	Calcite	Gray	Pinkish gray	Coarse	Massive	Hammer mill	Do.
35	Friendsville, Tenn.	do	Pink	Weak pink	do	do	Jaw; grinder; rotary.	Do.
36	do	do	Dark cedar	Weak purplish red	do	do	do	Do.
37	Concord, Tenn	do	Cedar	Dusky red purple	do	do	Hammer mill	
38	do	do	Gray	Pinkish gray	do	do	do	
39	do	do	Pink	Moderate pink	do	do	do	
40	Llano, Tex	Serpintine	Green	Dusky yellow green.[7]		Veined	Jaw; hammer mill; cone.	Square.
41	do	Dolomitic	Blue	Dark bluish gray [8]	Medium	Massive [18]	do	Do.
42	do	Dolomite	White	Light bluish gray [9]	Fine	do [18]	do	Do.
43	do	Serpentine	Green	Weak yellow green.[10]		Veined	Jaw; hammer mill; roller.	Do.
44	do	Dolomite	Blue	Medium bluish gray.	Medium	Stratified	do	Do.
45	do	do	White	Yellowish gray	Coarse	Massive	do	Do.
46	Marble Falls, Tex	Hematitic dolomite.	Red	Dusky red	Fine	do [18]	Jaw; hammer mill; cone.	Do.
47	do	do	Salmon	Weak reddish brown. [11]	do	do [18]	do	Do.
48	do	Dolomitic	Red	Pale reddish brown	do	do [18]	do	Do.
49	do	Calcite	Cream	Yellowish gray	do	do [18]	do	Do.
50	do	Carbonaceous calcite.	Black	Dark gray	do	Stratified	do	Do.
51	do	Dolomitic	Pink	Very pale brown	do	Massive	Jaw; hammer mill; roller.	Do.
52	do	Carbonaceous calcite.	Black	Dark gray	do	Stratified	do	Do.
53	do	Calcite	Yellow	Dark yellowish orange.	do	do	Jaw; hammer mill; cone.	Do.
54	Bertram, Tex	Siliceous calcite	do	do	Coarse	Massive	Jaw; hammer mill; roller.	Do.
55	do	do	Red	Pale reddish brown	do	do	do	Do.
56	Sudduth, Tex	Dolomitic	Pink	Reddish gray	Fine	do [16]	Jaw; hammer mill; cone.	Do.
57	do	Calcite	Brown	Moderate reddish brown.	Coarse	Stratified	do	Do.
58	Burnett, Tex	do	Red	Moderate pink [12]	Fine	Massive [21]	Jaw; hammer mill; roller.	Do.
59	do	do	Cream	Very palebrown	do	do [18]	do	Do.
60	Sipe Springs, Tex	Hemititic calcite	Red	Moderate reddish brown.	do	do	do	Do.
61	do	Calcite	Amber	Moderate brown	do	do	do	Do.
62	Oak Hill, Tex	do		Weak yellowish orange.	do	do	do	Do.
63	Hooper, Tex	do	Cream	Very pale brown	do	Stratified [19]	Jaw; hammer mill; cone.	Do.
64	Longhorn Cavern, Tex.	do	Sienna	Light yellowish brown.	do	Massive [18]	do	Eo.

See footnotes at end of table.

Table 1.—*Description of raw materials and fabrication processes*—Continued

Sample number	Source and description of raw materials						Equipment used for crushing and grading	
	Source	Classification	Color		Texture	Structure	Type of crushers	Types of sieve openings
			Producer's designation	ISCC-NBS [1] designation				
65	Middlebury, Vt	Calcite	White	White	Fine	Veined	Gyratory; roller	Square.
66	Brandon, Vt	Dolomitic	Pink	Weak red purple	do	do	do	Do.
67	do	do	do	Weak orange pink orange.	do	do	do	Do.
68	do	do	Cream	Weak yellowish orange.	do	do	do	Do.
69	Swanton, Vt	Hematitic dolomite.	Red	Moderate reddish brown [13].	do	Massive	Gyratory	Round.
70	Roxbury, Vt	Serpentine	Green	Very dusky blue green.		Veined	do	Do.
71	Danby, Vt	Calcite	White	White	Coarse	do	do	Do.
72	Isle LeMotte, Vt	Carbonaceous calcite.	Black	Dark gray	Fine	Stratified	do	Do.
73	Pittsford, Vt	Calcite	White	White [14]	do	Veined	do	Do.
74	Harrisonburg, Va	Carbonaceous calcite.	Black	Dark gray	do	Stratified	Hammer mill	Do.
75	do	do	do	do	do	do	Jaw; gyratory	Do.
76	Italy	Calcite		Weak yellow	do	Massive [18]	Gyratory	Do.
77	do	do		Yellowish gray	do	Stratified	do	Do.

[1] Inter-Society color council-National Bureau of Standards.
[2] Occasional white spots.
[3] Light gray veins.
[4] Light gray areas.
[5] Light gray veins.
[6] Frequent light yellowish brown areas.
[7] Weak yellow green veins.
[8] Light gray veins.
[9] White veins.
[10] Dark gray specks.
[11] White and medium gray veins.
[12] Frequent moderate yellowish orange areas.
[13] Frequent light gray spots.
[14] Medium gray veins.
[15] Frequent white chalky inclusions.
[16] Irregular fractures.
[17] Cellular structure (travertine).
[18] Irregular fractures, mostly healed.
[19] Some cellular portions.
[20] Frequent brown chalky lenses.
[21] Yellowish calcite pebbles in a pink ground mass.

1. Color

Most aggregates on the market have trade designations based on color, but in order to convey a more accurate conception of the differences between the so-called reds, greens, yellows, etc. from various sources, more specific terms are desirable. The method [1] used in designating the color terms in column 5 of table 1 has been employed in several other fields.[2]

In column 4 of table 1 are given the producers' color designations, so far as they indicate a color. Where a producer has two or more shades of one color, his designation usually distinguishes between them by such terms as "light green" and "dark green." These terms are sufficient to distinguish the colors of these particular products, but his light green may differ greatly from some other producer's light green. The terms in column 5 are intended to overcome this objectionable feature of trade designations by rating all the samples by reference to a single standard, and the following is a brief outline of the method used.

The first step was to determine the Munsell notation of the color by visual interpolation on the Munsell color scales. A gray mat with perforations was used to give a uniform background, and the interpolations were made by viewing the samples and scales perpendicularly with daylight striking them at 45 degrees.

From the Munsell notation for each sample the color designations were found by means of charts showing the standard designations apply-

[1] Deane B. Judd and Kenneth L. Kelly, *Method of designating colors*, J. Research NBS **23**, 355 (1939) RP1239.

[2] Delegates from the following national groups have approved the method of color designations recommended by the Inter-Society Color Council for the description of drugs and chemicals:

American Association of Textile Chemists & Colorists.
American Ceramic Society.
American Psychological Association.
American Society for Testing Materials.
Illuminating Engineering Society.
National Formulary, American Pharmaceutical Association.
Optical Society of America.
Technical Association of the Pulp & Paper Industry.
United States Pharmacopoeial Convention.

This method has also been adopted by the United States Department of Agriculture for the description of the colors of soils (T. D. Rice, Dorothy Nickerson, A. M. O'Neal, and James Thorp, Preliminary Color Standards and Color Names for Soils, U. S. Department of Agriculture Misc. Pub. 425), and it is one of the provisions of the American War Standards (Z44–1942) for the specification and description of color.

ing to various ranges of Munsell hue, value, and chroma. Each designation applies to a considerable color range. Furthermore, colors falling on boundaries of these ranges may take any of the contiguous terms. The color terms used in table 1 apply to the predominant colors of the samples. Mottled or prominently veined samples are described more specifically by the footnotes to table 1.

2. Mineralogical Classification

Classification of the materials was determined for most samples from the results of such physical tests as density, hardness, and absorption, along with etching tests with cold dilute acids. In a few instances where such means did not give conclusive results, thin sections were made for microscopic examination, and for two samples it was necessary to make partial chemical analyses. The samples composed mainly of calcium carbonate were classified as calcites, and those near the theoretical composition $CaMg(CO_3)_2$ were called dolomites. Several samples were intermediate between calcites and dolomites, and these were called dolomitic marbles. Impure materials like the black marbles or the highly siliceous varieties were indicated by modifying terms, such as carbonaceous or arenaceous, to denote the nature of the main impurity. All the green samples were classified as serpentines (hydrous silicates of magnesia and iron). Of the 77 samples included in this study, 44 were calcites, 9 dolomites, 16 dolomitic marbles, and 8 serpentines.

3. Texture

The marbles were graded into three textures, namely fine, medium, and coarse, depending on the grain diameter. The system recommended by Dale [3] was followed, except that all grades with maximum grain diameters less than 0.75 mm were designated "fine", and all with maximum grain diameters of 1.5 mm or greater were designated "coarse." No attempt was made to grade the serpentines because of their variability. The mineral serpentine is fibrous, but the rock is usually a mixture of serpentine with other minerals, such as magnetite, pyrite, hornblende, talc, calcite, dolomite, and magnesite, the carbonates commonly forming the white veining material.

4. Structure

Structure refers to the arrangement of the mineral constituents. The common terms "stratified" (parallel arrangement) and "massive" (no definite arrangement in layers) are applicable to the greater portion of the samples. Some marbles show no definite signs of stratification but contain veining matter of different color or composition from that of the main portion. The serpentines are good examples of such structure, but it is often found in calcites or dolomites. Although these are massive rocks, their structures are better defined by the term "veined." Two samples, numbers 14 and 15 in table 1, contain frequent parallel layers of talc along which the rock can be easily split. Such structures are defined as "laminated."

5. Fabrication

Preparation of aggregates for the market is a three-stage operation, namely removal of the rock from the quarry, crushing, and grading. Where the rock is used only for aggregate, the common means of removal from the ledge is blasting. Quarries producing building stone use channeling machines to remove large blocks from the ledge. These large blocks are then sawed in slabs or smaller blocks, and only the waste material is crushed for aggregate. Crushing machines are of six types, namely gyratory, jaw, hammer mill, roller, ring, and cone. Some producers do the crushing in one operation, but most of them do it in two stages. The primary crushing is ordinarily done with a jaw or gyratory crusher and the final with a hammer mill or roller.

After crushing the rock, it is necessary to remove the fine particles and grade the chips into three sizes, as follows: No. 1 aggregate

[3] The Commercial Marbles of Western Vermont, U. S. Geological Survey Bulletin 521 (1912).

passes a ¼-in. sieve and is retained on the ⅛-in. sieve; No. 2 passes a ⅜-in. sieve and is retained on the ¼-in. sieve; No. 3 passes the ½-in. sieve and is retained on the ⅜-in. sieve. Chips smaller than ⅛-in. are not used in terrazzo. Sieves are of two types, namely round hole and square hole. Round-hole sieves are made of sheet metal with circular perforations, and square-hole sieves are made of wire mesh.

III. DESCRIPTION OF TESTS

1. Wear Resistance

Abrasion tests were made with the apparatus shown in figure 1.[4] This consists essentially of a power-driven grinding lap, *A*, 10 in. in diameter, which is revolved at 45 rpm; three specimen holders, B, with superimposed weights, and gears, *C*, for revolving the specimen; and a means of feeding abrasive at a constant rate to the lap. The guide rings, *D*, are clamped in position slightly above the specimen holders, and the 2,000-g weight bearing on the specimen is the combined weight of the specimen holder, vertical shaft above with the attached spur gear, and a weight hopper, *E*, containing additional adjustment weights. The frame, *F*, carrying the guide rings is adjustable vertically to accommodate different specimen thicknesses. Gears, *C*, are adjusted on the shafts for each specimen thickness, so they are slightly above the plate, *G*, throughout the test.

The test specimens were 2 by 2 by 1 in., and eight were prepared from each sample in such a way as to give the wear resistance for two directions perpendicular to each other. For stratified materials, four specimens were prepared with the 2- by 2-in. faces (those abraded)

[4] D. W. Kessler, *Wear resistance of natural stone flooring.* BS J. Research **11**, 635 (1933) RP612.

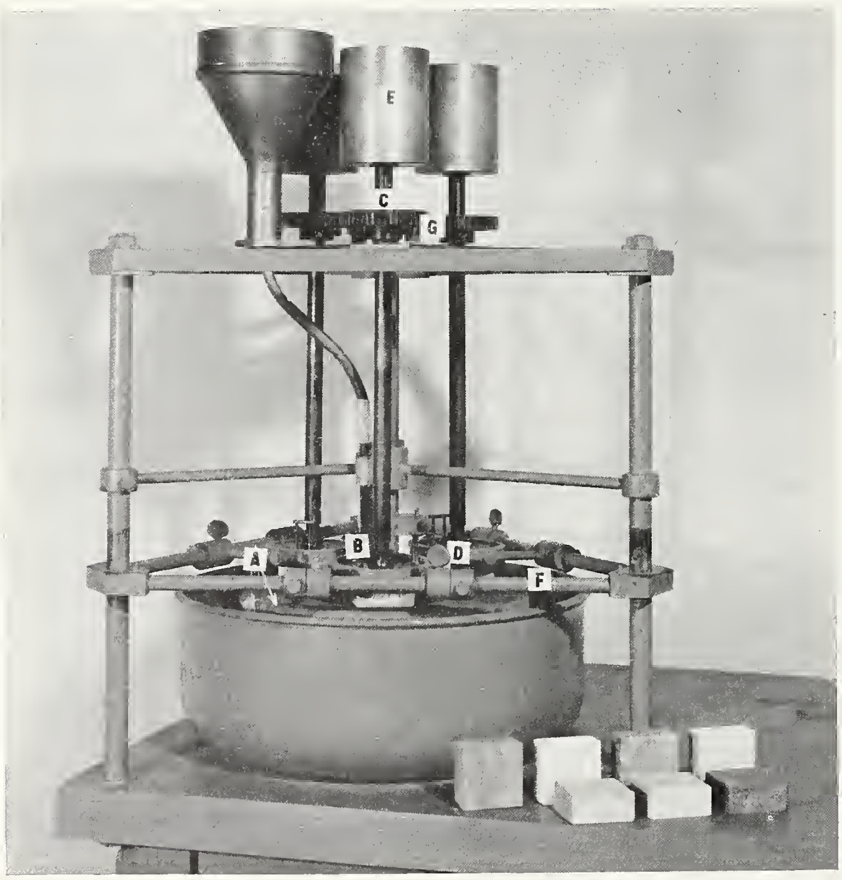

Figure 1.—*Apparatus used for determining resistance to abrasion.*

parallel to the bedding direction and four others with these faces perpendicular to the bedding. For samples showing no stratification, half of the specimens were cut with the test faces parallel to some arbitrary direction and the others perpendicular to that direction.

After the specimens were dried at 105±2° C and weighed, one was inserted in each specimen holder and abraded with No. 60 artificial corundum for 225 turns of the lap. The final weights were determined, and the wear resistance (H_a) was computed by the formula

$$H_a = \frac{10G(W_s+2000)}{2000\ W_a},$$

in which G is the bulk specific gravity, W_s is the average weight of the specimen (original weight plus final weight divided by 2), and W_a is the difference between the original weight and final weight of specimen. The results are expressed as reciprocals of the volume abraded in order to give values in the same order as those commonly used for expressing the hardness of minerals.

2. Toughness

The resistance to impact, commonly called toughness, was determined with the apparatus shown in figure 2. It consists of a heavy iron base, *A*, with a device for holding the specimen, *B*. The plunger, *C*, is held in position in the sleeve, *D*, and the lower end rests on the specimen. *E* is a 2-kg weight which drops on the plunger from variable heights until the specimen breaks. The test procedure (Standard Method of Test for Toughness of Rock ASTM Designation D 3–18) followed in this study was to drop the weight from successive heights of 1, 2, 3, or more centimeters until the specimen broke, and the height of the last drop was taken as the toughness index. The operation is mechanical except that the operator controls the height of each drop of the weight with the crank, *F*.

The tests were made on two cylindrical specimens 1 in. high and 1 in. in diameter cored from each sample. The stratified samples were cored with the axis of specimens perpendicular to the bedding, whereas the others were cored in any convenient direction. The ends of the cores were finished by grinding them to smooth, parallel surfaces. Before the tests were made the cores were dried for 24 hr at 105° C. Since the lower end of the plunger is rounded, it has a mild chiseling action, which usually splits the specimen in two or three pieces, as shown by the broken specimens in figure 2.

3. Absorption

The 2- by 2- by 1-in. specimens prepared for the abrasive-resistance tests were used for absorption and bulk specific gravity determinations before the abrasion tests were made. These blocks were dried for at least 18 hr at 105°±2° C, cooled, and weighed to the nearest 0.01 g, then totally immersed in water at 20°±5° C for 48 hr. They were then removed from the bath, surface dried with a towel, and weighed again.

The results are computed by the formula

$$\text{Absorption } (\%) = \frac{W_2 - W_1}{W_1} \times 100,$$

in which W_1 is the dry weight of the specimen, and W_2 is the weight of the specimen after soaking it for 48 hr.

4. Bulk Specific Gravity

After the final weighing for the absorption test, the specimens were again immersed in water to maintain them in a soaked condition until their volumes could be determined. This was done by weighing them suspended in water. The bulk specific gravity was computed by the formula

$$G = \frac{W_1}{W_2 - W_3},$$

in which W_3 is the weight of the specimen suspended in water. No density corrections were applied for the water temperatures, since a high degree of accuracy was not necessary.

516850—43——2

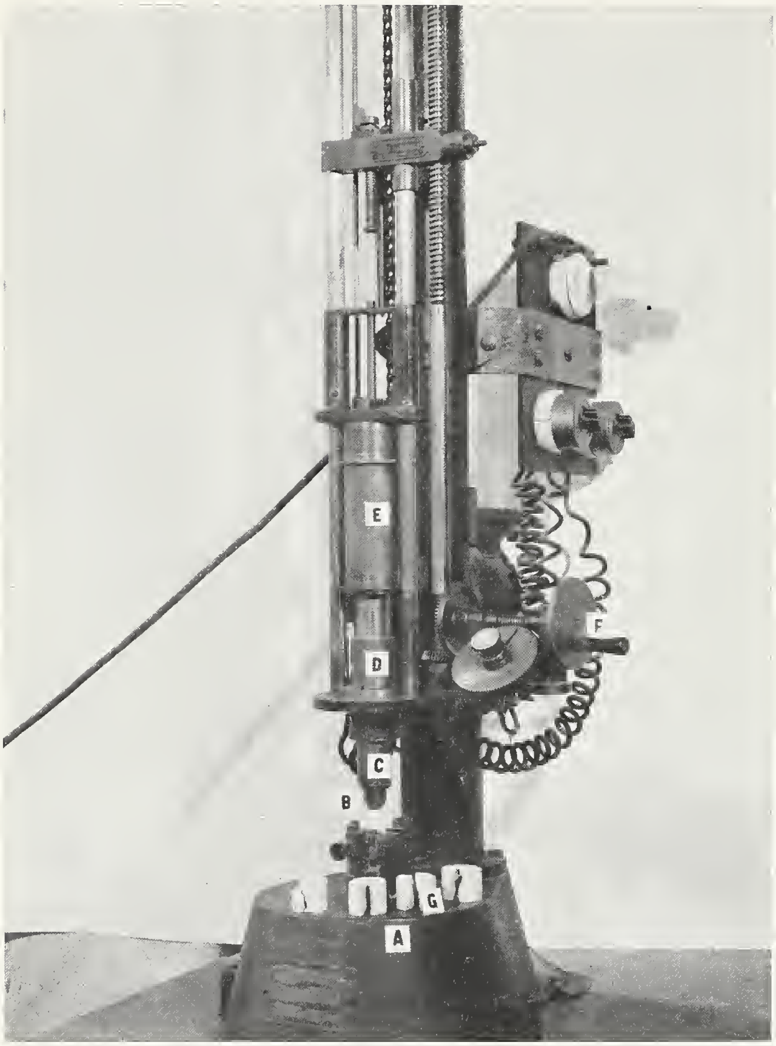

Figure 2.—*Toughness apparatus used for determining resistance to impact.*

5. Dust Content

The dust content, i. e., the portion of the sample that could be washed through a No. 100 sieve, was determined on samples of No. 2 aggregate. The entire sample received from the producer was used, because it was found very difficult to mix the sample so the dust would be uniformly distributed through all portions, and for this reason the samples varied in weight from about 1 to 5 lb. After drying the sample at $105° \pm 2°$ C and weighing it to the nearest 0.01 g, it was placed on a No. 8 sieve nested in a No. 100 sieve. The sample was then washed with a stream of water until the water passing through the lower sieve ran clear. The sieves and their contents were then thoroughly dried and the material on them weighed. The dust, i. e., the difference between the original and final weights of the samples, is expressed as a percentage of the original dry weight.

6. Percentage of Voids

This determination was made on samples of the aggregate averaging about 1 lb in weight. A glass measure was made for this purpose by cutting off the top of a Pyrex beaker, then grinding the top edge until a ground-glass cover plate made perfect contact at all points. The volume of the container was determined by first weighing it empty, then full of water, and finally dividing the weight of the water by its density. The percentage of voids of the samples were determined for two methods of filling the measure: (1) pouring the aggregate slowly from a height of about 10 in. while the measure was rotated slowly, and (2) by fastening a strong paper around the measure so that it extended 1 in. above the top, filling with aggregate to the top of the paper, then vibrated on the table of a vibrating machine for 10 min. In both methods the excess aggregate was carefully leveled off until the cover plate made contact with the top of the measure at all points without being pressed down. In the vibration method the measure was set on a rubber mat on the vibrator table (frequency 3,450 cycles/min, and amplitude 0.003 in.) and held in place by a ring slightly larger than the outside diameter of the measure.

The weight of aggregate required to fill the measure was divided by the bulk specific gravity of the sample to obtain the volume of the particles. The difference between the volume of the measure and that of the particles gave the void space. The results are expressed as a percentage of the bulk volume of the material.

7. Thickness Grading

A special type of sieve was constructed for this test, consisting of a box about 8 in. square and 1 in. deep. The bottom and two sides were made of ⅛-in. brass plates, and the other two sides were wood. The brass sides were adjustable vertically so that slots of any desired width could be formed with the bottom plate. By means of gage blocks the slot width was made 3/16 in. for the first test, ⅛ in. for the second, and 1/16 in. for the third. It was found that the slot width for any one setting did not vary more than 0.003 in. at any point from that of the gage thickness.

The specimens used in the thickness-grading tests were obtained by thoroughly mixing the entire sample on a large sheet of strong paper, quartering, and taking diagonally opposite quarters. The slots were first adjusted to 3/16 in., and a 200-g sample was put on the sieve and sieved by hand with a rotary motion, first sieving from one slot and then the other to avoid clogging as far as possible. The part remaining on the sieve was weighed. The slots were then set to ⅛ in., and the part passing through the 3/16-in. slot was resieved as in the first operation. This was followed by resieving with the 1/16-in. slot the part passing the ⅛-in slot. The weight of each fraction is expressed as a percentage of the entire specimen.

8. Dimensional Changes

(a) *Moisture Effects*

Linear measurements were made at controlled temperature (73° ±2° F) on a few specimens while they were absorbing water and also while drying. A Tuckerman optical strain gage [5] reading to 0.000002 in. was mounted along the diagonal of the 2′ by 2′ by 1-in. specimen, giving a gage length of 2 in. The dried specimen was laid on microscope slides in a glass dish and, after taking the original reading, a sufficient amount of water was poured in the dish to bring the level about one-third of the way to the top of the specimen. Readings of the gage were taken at 2-hr intervals during the first 8 hr. and at convenient intervals during the days following. When no further expansion occurred the water level was raised nearly to the top of the specimen and readings continued until the maximum expansion was recorded. The water was then syphoned off, and readings were made during the drying period until the minimum was reached.

(b) *Temperature Effects.*

Linear expansions were measured at controlled humidity over the temperature interval −24° to +60° C by the interferometer method.[6] The specimens were made in the form of a tripod with legs averaging about ¼ in. in height. These were dried at 105° C and

[5] L. B. Tuckerman, *Optical strain gages and extensometers*, Proc. Am. Soc. Testing Materials, **23**, pt. 2, 602 (1923).

[6] G. E. Merritt, *The interference method of measuring thermal expansion*, BS J. Research **10**, 59 (1933) RP515. J. B. Saunders, *Improved interferometric procedure with application to expansion measurements*, NBS J Research **23**, 179 (1939) RP1227.

put between fused quartz plates in a specimen chamber, the humidity of which was maintained at a low level by means of a desiccant. Specimens of stone usually expand at a higher rate than fused quartz, and hence some horizontal slippage occurred between the two materials as the temperature was varied. By weighting the upper quartz plate with a small U-shaped bar of lead over the leg of the specimen near the reference point where measurements were made, the slippage was confined to the other two points of contact. The temperature was lowered to −24° C for the first reading and raised at the rate of 1° C each 3 min. Expansion readings were made at about 7° C intervals. After the reading at +60° C was obtained, the temperature was then lowered at a rate of 1° C in 3 min until 0° C was reached, contraction readings being made at appropriate intervals.

IV. RESULTS OF TESTS

The results of the physical tests on the rock in its original condition and on the crushed material are given in tables 2 and 3.

Table 2.—*Results of tests on the original rock*

Sample number	Abrasive resistance (H_a)						Bulk specific gravity	48-hr absorption	Toughness
	Direction *A*			Direction *B*					
	Max.	Min.	Avg.	Max.	Min.	Avg.			
								Pct.	
1	16.2	12.7	14.7	16.7	12.8	14.8	2.71	0.10	6
2	18.8	17.1	17.8	19.7	16.7	18.6	2.76	.84	6
3	----	----	----	----	----	----	2.74	1.06	----
4	31.0	19.1	23.9	30.7	16.9	21.5	2.72	0.56	9
5	14.2	6.8	10.0	9.7	7.9	8.9	2.23	4.00	4
6	33.6	27.8	31.4	34.7	29.0	31.4	2.77	0.07	12
7	30.2	26.1	28.5	33.6	30.2	32.1	2.74	.67	6
8	30.5	21.8	25.6	29.6	26.5	28.1	2.74	.58	10
9	36.4	30.1	33.1	35.7	30.2	33.4	2.69	.36	4
10	30.7	26.6	28.5	29.2	25.9	28.1	2.76	.84	17
11	24.7	22.7	24.0	23.9	21.2	22.4	2.66	1.88	10
12	25.9	21.6	23.0	25.0	22.5	23.5	2.65	0.18	8
13	24.4	21.1	22.8	25.9	21.2	23.3	2.70	.22	6
14	10.6	6.5	8.9	18.7	16.5	17.9	2.84	.21	6
15	19.8	14.5	16.0	30.3	26.9	28.3	2.84	.08	9
16	47.3	34.1	41.5	63.0	45.0	52.8	2.61	1.37	8
17	52.7	43.4	47.1	53.7	36.9	43.6	2.71	0.40	6
18	10.6	9.3	10.0	13.5	12.0	12.6	2.86	.12	3
19	17.0	13.3	15.3	----	----	----	2.71	.13	----
20	17.6	15.6	16.6	17.1	14.9	15.7	2.63	2.02	4
21	14.0	9.8	12.3	----	----	----	2.51	2.67	3
22	17.1	15.1	16.0	20.9	17.4	18.9	2.67	0.29	6
23	19.3	16.9	18.4	20.2	16.9	19.0	2.63	.80	4
24	32.0	25.8	29.8	32.0	25.3	28.6	2.69	.36	6
25	35.4	30.3	32.5	33.5	25.7	30.4	2.68	.29	6
26	29.7	23.4	25.9	30.6	22.5	26.8	2.67	.41	5
27	30.2	21.5	25.0	28.1	22.3	24.3	2.52	2.00	5
28	39.5	28.3	35.3	33.9	27.7	31.1	2.65	0.96	5
29	19.3	13.9	16.8	19.1	13.2	16.7	2.68	.26	4
30	70.0	59.8	63.6	66.7	56.3	61.0	2.64	.46	24
31	22.6	18.0	20.2	25.2	22.4	23.7	2.82	.37	4
32	61.4	53.4	58.5	64.4	52.5	57.5	2.66	.05	19

Table 2.—*Results of tests on the original rock*—Con.

Sample number	Abrasive resistance (H_a)						Bulk specific gravity	48-hr absorption	Toughness
	Direction *A*			Direction *B*					
	Max.	Min.	Avg.	Max.	Min.	Avg.			
33	39.3	24.1	31.8	35.0	30.0	33.1	2.65	.13	14
34	22.5	18.9	21.2	24.3	17.9	21.8	2.70	.09	5
35	24.6	20.2	22.1	24.0	20.1	21.9	2.70	.08	4
36	25.0	23.3	24.1	26.2	21.4	25.0	2.72	.06	6
37	25.5	22.3	23.9	23.9	21.9	22.9	2.72	.08	6
38	25.3	20.2	23.0	24.7	20.9	23.1	2.70	.08	4
39	29.5	25.8	27.6	27.5	24.0	25.5	2.71	.08	6
40	14.4	10.9	12.3	19.8	12.9	15.6	2.39	3.23	8
41	14.3	12.5	13.4	17.4	15.3	16.2	2.81	0.14	6
42	33.3	30.2	32.1	30.8	20.3	25.0	2.98	.04	8
43	10.4	9.6	10.0	9.9	8.7	9.3	2.20	7.43	4
44	16.9	11.9	13.4	17.0	11.3	14.1	2.87	0.06	4
45	21.2	14.8	18.1	20.4	15.4	18.2	2.89	.07	6
46	44.5	33.3	38.9	41.8	36.7	39.9	2.81	.38	7
47	49.4	38.8	43.0	47.7	36.8	41.0	2.81	.34	12
48	40.5	36.2	39.6	42.8	38.0	40.5	2.79	.47	16
49	46.8	41.5	44.0	55.8	42.7	48.9	2.69	.20	4
50	79.7	61.0	70.7	77.0	60.7	66.9	2.64	.43	33
51	30.5	27.7	29.6	30.3	28.1	29.1	2.81	.11	12
52	94.7	69.4	78.3	83.6	61.4	76.7	2.62	.27	34
53	27.4	18.6	24.1	28.4	20.5	24.8	2.56	2.02	8
54	20.8	17.2	18.8	20.8	17.5	18.8	2.61	1.50	6
55	21.1	16.0	18.0	19.1	18.1	18.4	2.60	1.68	5
56	26.7	20.4	24.2	31.0	26.0	28.1	2.79	0.24	8
57	25.9	22.7	23.7	26.6	22.2	24.7	2.69	1.27	5
58	32.1	26.6	29.6	32.3	22.8	27.4	2.67	0.59	6
59	51.8	46.3	48.6	51.8	46.8	48.6	2.71	.08	6
60	31.6	27.8	29.2	33.3	30.5	32.1	2.64	.86	8
61	35.8	30.0	32.8	36.4	27.3	33.1	2.64	.58	12
62	35.8	30.8	33.5	41.2	36.5	38.4	2.66	.60	8
63	31.4	26.1	29.1	32.1	24.0	27.6	2.60	1.28	8
64	43.1	37.1	40.7	42.5	37.1	40.8	2.70	0.11	6
65	22.4	17.2	19.8	22.1	20.5	21.3	2.70	.09	4
66	39.3	26.3	32.5	32.8	28.1	30.6	2.81	.18	7
67	34.2	26.1	31.4	32.4	29.3	31.0	2.82	.19	8
68	36.5	28.1	31.6	38.8	31.3	35.0	2.81	.25	12
69	40.0	34.6	36.6	37.4	30.4	34.6	2.83	.11	20
70	108.0	94.2	99.9	126.5	103.9	112.2	2.68	.14	34
71	14.3	11.1	12.8	16.7	11.7	13.8	2.71	.10	3
72	30.0	25.9	29.0	29.5	27.1	28.0	2.78	.16	10
73	19.1	14.3	15.9	23.1	15.5	18.4	2.73	.13	4
74	37.8	33.5	36.0	32.6	30.0	31.6	2.72	.03	6
75	38.8	34.1	36.6	33.6	30.6	32.0	2.72	.04	5
76	42.8	39.4	41.1	41.0	38.4	40.0	2.71	.13	6
77	23.3	15.6	19.5	20.1	16.8	18.9	2.46	.98	4

Table 3.—*Results of tests on No. 2 chips*

Sample number	Dust content	Void space		Amounts of chips of stated thickness			
		Loose	Vibrated	Less than 1/16 in. (T_1)	1/16 to 1/8 in. (T_2)	1/8 to 3/16 in. (T_3)	Greater than 3/16 in. (T_4)
	%	%	%	%	%	%	%
1	0.87	45.07	41.12	----	----	----	----
2	.44	45.82	43.09	0.25	13.50	43.38	42.81
3	.47	45.23	41.55	.14	7.32	38.11	54.31
4	.27	44.16	40.35	.42	9.52	41.23	48.80
5	1.25	39.75	36.63	----	----	----	----
6	0.21	44.94	40.94	----	----	----	----
7	.45	43.13	40.59	.65	10.02	37.38	51.92
8	.29	45.93	41.87	.32	9.36	35.03	55.25
9	.16	42.64	39.28	.23	5.64	46.56	47.57
10	.22	44.32	40.94	.27	6.48	28.29	64.95
11	.33	41.93	38.34	.22	8.34	37.09	54.37
12	.33	42.28	38.83	----	----	----	----
13	.42	46.33	42.27	----	----	----	----
14	.37	44.36	40.62	.24	16.84	57.31	25.57
15	.76	45.58	41.34	.53	18.10	49.05	32.28
16	.61	48.00	43.31	----	----	----	----
17	.37	53.61	50.14	----	----	----	----
18	1.83	42.56	38.26	2.97	6.41	20.30	70.31
19 [a]	----	----	----	----	----	----	----
20	0.28	47.08	43.55	----	----	----	----
21	1.47	46.86	40.32	----	----	----	----

Table 3.—*Results of tests on No. 2 chips*—Continued

Sample number	Dust content	Void space		Amounts of chips of stated thickness			
		Loose	Vibrated	Less than 1/16 in. (T_1)	1/16 to 1/8 in. (T_2)	1/8 to 3/16 in. (T_3)	Greater than 3/16 in. (T_4)
	%	%	%	%	%	%	%
22	0.55	46.58	42.31	---	---	---	---
23	.74	46.52	42.94	---	---	---	---
24	.40	43.74	40.32	---	---	---	---
25	.46	44.01	39.62	1.00	4.59	26.51	67.89
26	.55	43.50	39.16	0.77	5.47	31.31	62.43
27	2.08	40.43	36.52	6.63	9.85	34.66	48.80
28	0.40	43.04	39.19	0.77	6.07	35.08	58.07
29	.52	44.89	41.17	---	---	---	---
30	.73	44.86	40.98	---	---	---	---
31	.45	44.68	41.46	.75	19.72	39.76	39.71
32	.30	45.02	42.00	---	---	---	---
33	.38	47.68	44.81	1.36	24.28	47.21	27.14
34	.73	45.35	43.42	---	---	---	---
35	.40	46.38	42.75	0.21	10.76	34.18	54.83
36	.28	45.04	41.17	.13	10.26	53.23	36.40
37	.31	44.88	42.61	.20	8.53	36.72	54.53
38	.33	44.60	42.80	.53	9.63	39.18	50.63
39	.39	44.37	42.70	.81	13.35	36.83	49.00
40	.62	46.10	42.14	1.66	18.52	41.77	38.02
41	.61	44.02	40.81	0.82	15.84	50.81	32.49
42	.44	44.95	41.53	---	---	---	---
43	.76	40.36	37.70	---	---	---	---
44	1.31	41.24	37.89	1.44	6.64	29.77	62.07
45	0.62	43.96	40.68	0.63	9.97	44.85	44.49
46	.25	45.16	41.72	.50	6.63	35.27	57.56
47	1.13	45.84	41.46	---	---	---	---
48	0.37	44.62	41.66	1.10	17.84	42.97	38.07
49	.38	43.06	40.45	1.17	16.80	51.35	30.66
50	.27	43.74	41.22	0.08	9.34	53.80	36.76
51	.41	45.86	42.58	.44	11.37	47.09	41.07
52	.45	47.55	43.96	---	---	---	---
53	.88	43.42	39.94	---	---	---	---
54	.54	46.20	41.60	.87	24.62	58.89	15.62
55	.30	45.39	41.11	.79	14.35	50.93	33.97
56	.27	43.19	39.95	.08	5.13	41.22	53.59
57	.69	44.78	41.02	---	---	---	---
58	.31	44.77	41.75	---	---	---	---
59	.17	44.04	41.15	.58	16.33	46.78	36.32
60	.26	45.03	42.62	1.23	19.80	52.32	26.67
61	.28	45.24	41.70	0.12	13.98	43.31	42.53
62	.46	44.67	40.90	---	---	---	---
63	.53	43.84	40.20	.92	17.96	50.52	30.64
64	.55	41.42	39.04	---	---	---	---
65	1.25	44.90	40.84	---	---	---	---
66	0.57	45.67	41.32	1.42	23.51	52.59	22.45
67	.32	44.81	41.52	2.42	33.15	54.02	10.37
68	.60	43.91	41.57	---	---	---	---
69	.33	46.35	42.57	0.90	16.23	37.22	45.65
70	.31	48.57	44.47	1.96	23.06	40.92	34.05
71	2.07	41.81	38.49	0.19	0.77	17.00	82.04
72	0.36	45.89	42.65	1.17	18.97	38.66	41.20
73	1.94	42.83	39.05	0.76	7.37	45.22	46.65
74	0.16	44.97	41.57	.04	4.79	49.84	45.33
75	.09	46.47	41.77	1.62	20.67	45.50	32.25
76 [a]	---	---	---	---	---	---	---
77	.43	44.29	40.38	0.21	11.81	45.60	42.38

[a] No sample of chips.

1. Wear Resistance

Among the aggregates studied, the serpentines, as a class, are shown to be the most resistant to wear, and in the calcite, dolomitic, and dolomite classifications there are no very appreciable differences in average values, these being, in round numbers for the order stated, 28, 26, and 25. There are rather large variations in all of these types, and although the serpentines have high resistance as a group, two samples in this series gave results much lower than the average of all classes. Serpentine is a weathered form of the original deposit and may be expected to be quite variable even in one quarry, depending on how near it is taken from the surface of the ground or to an open joint where it is exposed to surface water.

In arriving at a suitable abrasive-resistance value for floors, one may consider the actual performance of marbles, which have been extensively used in tile form for a considerable period of time. One variety of marble in this series has given satisfactory service in such buildings as the Grand Central Station, New York City, for more than 25 yr. The H_a values obtained for this marble are in the range 18 to 22. It may be assumed, therefore, that aggregates giving such test values will prove to be durable in terrazzo under severe conditions of foot traffic. The average H_a value of all the aggregates tested is considerably above 20, and hence the wear resistance of the greater portion of these should be satisfactory. One marble gave a test value below 9 in one direction (parallel to the lamination) and a value nearly 100 percent higher at right angles to that direction. Few of the aggregates showed any appreciable difference in the two directions. When two or more aggregates are combined for color effects, one is apt to differ considerably in hardness from the other. In such mixtures the rate of wear on the floor will probably be governed by the most resistant portion.

2. Toughness

The results of toughness tests given in table 2 show the relative resistance of the materials to impact and give a measure of the coherence of the components. The average toughness for the 75 samples tested was 8 and the range from 3 to 34. This test has been extensively used on paving materials, and the following average values for different types of rock reported by the United States Bureau of Public Roads [7] are of interest. Trap rocks, including andesite, basalt, diabase, and rhyolite have an average toughness of 18; gabbros, 14; granite, 8; limestone, sandstone, and marble, 7; and quartzite, 15.

[7] Prevost Hubbard and Frank H. Jackson, Jr., Results of physical tests of road building rocks, U. S. Department of Agriculture Bulletin 370 (1916).

In materials of low coherence the individual grains or crystals may be dislodged under abrasion and, hence wear away more rapidly than materials with the same mineral constituents having a higher degree of coherence. It may be noted that all the samples giving toughness values above 20 were very resistant to abrasion, regardless of their mineral compositions. One of these samples was a serpentine, one a dolomitic marble, and two were calcites.

Correlations between the toughness and H_a values for materials of low toughness are not very satisfactory. For floors subjected only to foot traffic, it is doubtful if the toughness of the aggregate is of much concern, but where heavy trucks are used, an aggregate of high toughness is desirable.

3. Absorption

The absorption of most marbles used as building stone is less than 0.5 percent, but the average of all samples in this series is 0.7 percent. Fifteen samples absorbed more than 1 percent, and eight, more than 2 percent. The sample giving the highest absorption of the series (7.43 percent) was a serpentine reported to have given unsatisfactory performance in terrazzo. High absorption in itself is not detrimental, and a better bond between aggregate and cement probably would be obtained with a moderately porous aggregate than with one of low porosity. Another point in favor of aggregates of higher porosity is the fact that they absorb some of the excess water from the fresh mixture and later contribute to better curing conditions. However, a very porous aggregate in terrazzo is apt to soil and to absorb stains more readily than one of low pore space. The absorption values in table 2 give some information on the relative porosities for different samples, but the actual porosity (percentage of pores by volume) is from 4 to 6 times the percentage absorption by weight.[8]

[8] Since the pores of such materials are usually about 50 percent filled in the absorption test, an approximation of the total pore space may be obtained by multiplying the absorption values in table 2 by twice the bulk specific gravity. Multiplying the absorption values by bulk specific gravity converts the percentage weight relation to a volume relation.

There seems to be no relation between the absorption and abrasive resistance for any of the classes of materials except serpentines. A correlation coefficient was calculated between these two properties for the eight serpentines, and the result was $r=-0.67$. This means that the serpentines of low absorption are usually more wear resistant than those of high absorption, but the degree of correlation is not sufficient to justify estimates of abrasive resistance from the results of absorption tests.

4. Bulk Specific Gravity

Bulk specific gravity was used in computing the abrasive resistance and void space values given in table 2. Bulk specific gravity values indicate the relative weights of the samples in their original condition, and they can be readily converted to weights per cubic foot by multiplying by 62.35. For example, sample 42 in its original state weighs 186 lb/ft^3. Sample 43, the lightest material tested, weighs 137 lb/ft^3. The dolomites are the heaviest materials in the series.

From the bulk specific gravity and void space of the crushed rock one may approximate the unit weight of the No. 2 aggregate by multiplying the weight of the solid rock by $1-(\text{void space}/100)$, thus: The weight per cubic foot of aggregate of sample 42 loose (not compacted) is approximately $186\times0.55=102$ lb; and that of sample 43 is $137\times0.596=82$ lb.

5. Dust Content

The average dust content in the 75 samples tested was 0.57 percent, and the range was 0.09 to 2.08 percent. Two samples contained more than 2 percent, 9 samples more than 1 percent, and 46 samples less than 0.5 percent of dust.

Dust particles clinging to the aggregate are considered to be undesirable because they interfere with the bond between cement and aggregate. Some of the dust from the original crushing operation clings to the aggregate and probably more is formed by grinding of the fragments together in shipping and handling. Experiments show that it is not possible to remove all the dust by dry sieving, and measurable amounts are formed in sieving some materials for a few minutes. The particles of most aggregates have sharp edges, but in some samples submitted for this study the particles were rounded somewhat like waterworn pebbles. This rounding was probably caused by abrasion in handling or shipping. Most aggregates with high dust content were those in the lower abrasive-resistance group or those having soft chalk or clay-like inclusions. Rounded particles should produce mixtures that are more easily worked than angular ones and thus offset, to some extent, a high dust content. The dust should not be considered as a serious objection, because it can be easily washed off the aggregate before mixing.

6. Percentage of Voids

The percentages of voids obtained on 75 samples of No. 2 aggregate by the two methods described in section III–6 are given in table 3. The average for all the samples was 44.7 percent for the "loose" method and 41.2 percent for vibrated samples. For the first method the range of values was from 39.8 percent (sample 5) to 53.6 percent (sample 17), and for the second 36.6 to 50.1 percent (same samples). Although the samples were labeled No. 2 aggregate (¼ to ⅜ in.), a considerable number of them contained large amounts of particles that would pass a ¼-in. square-hole mesh. On a few samples, tests were made with mixtures of No. 1 (⅛ to ¼ in.) and No. 2 aggregates in equal portions to obtain comparisons with results on No. 2 alone. The voids in such mixtures were from 1 to 2 percent lower than for No. 2 aggregate alone.

These values indicate that for most aggregates, the usual mixtures, namely 1 bag of cement (1 ft^3) to 2 ft^3 of aggregate, provides a considerable excess of cement paste over that necessary to fill the voids of the aggregate. In cases where the quantities are proportioned by weight, appreciable variations in the volume ratios will occur for different aggregates. For example, consider two mixtures, one made with aggregate *A* (bulk specific gravity=2.20 and voids=40 percent), and the other made of aggregate *B* (bulk specific gravity=2.87 and voids=41 percent). The weight per cubic foot of aggregate *A* is $62.4\times2.20\times0.60$, or 82.4 lb, and the weight of *B* is $62.4\times2.87\times0.59$, or 105.7 lb. Hence 200 lb of aggregate *A* would be 2.44 ft^3 and of *B*, 1.89 ft^3. The actual volume of voids in aggregate *A* would be 2.44×0.40, or 0.98 ft^3, and in *B* 1.89×0.41, or 0.77 ft^3. One bag of cement would provide an excess of paste in either case, but for aggregate *B* there would be considerably more excess.

The rolling operation is assumed to remove, to some extent, the excess paste, but since cracking is reported to occur more frequently when certain aggregates are used, it may be assumed that the shape of particles has some effect on the amount of paste that can be worked out of the mixture. It is a well-established fact that rich mixtures shrink more than lean ones,[9] and where monolithic terrazzo floors crack excessively, the most plausible explanation therefor is, that the mixture was too rich.

It was apparent from examinations of several aggregates with high voids, that the shape of particles as well as gradation of sizes has a marked effect on the void content. Appreciable amounts of elongated, thin, or irregularly shaped chips increase the voids, and equidimensional particles in various sizes decrease the voids. The sample with the highest percentage of voids had many slender particles up to 1 in. in length but consisted mainly of flat shapes. One sample that consisted of very irregular particles with rough faces and almost free of elongated or flat chips had a high percentage of voids.

7. Thickness Gradings

Since the results of the foregoing tests do not afford any satisfactory explanation of the cause of failure reported by terrazzo workers for certain aggregates, it was decided to study the variations in the shapes of particles for the

[9] Max Gary, Trans. Am. Soc. Civil Engrs. **30**, 16. (1893).
M. Considere, Compt. rend. **129**, 467 (1899).
E. D. Campbell and A. H. White, J. Am. Chem. Soc. **28**, 1273 (1906).
J. Bauschinger, Mitth. Mech. Tech. Lab. d. Tech. Hochschule in Munchen 8th Heft. (1879).
J. C. Pearson, Eng. Contract Record **55**, 187 (1921).

different samples. British[10] and American[11] specifications for crushed stone to be used in bituminous concrete require that the aggregate be free of excessive flat or elongated pieces. Although there appears to be no tangible proof that such shapes cause undesirable results, it is inferred that this requirement is based on experience. Methods for determining the amounts of flat and elongated pieces of crushed stone have been devised at the Department of Scientific and Industrial Research[12] (London).

These methods are not well adapted for use on terrazzo aggregate sizes, since they involve the hand gaging of individual pieces, which would prove to be too tedious for terrazzo chips. Although sieves with various widths or elongated holes have been used for separating samples into various thicknesses of particles, it was considered more feasible to construct one sieve with adjustable slots, as described in section III–7, p. .

The proportions of particles of four thicknesses are given in table 3 for 48 samples. The other samples were found to be poorly graded and contained too much fine material to conform even approximately to No. 2 chips. The tabulated results are sufficient to show that marked differences exist between certain aggregates with respect to the amounts and distribution of particles of certain thicknesses. In a majority of the samples the amount of very thin chips was below 1 percent, but four contained more than 2 percent of this grade. These results show at least four types of distribution, as illustrated by graphs *A* to *D* in figure 3.

Graph *A* shows the grading of a sample for which terrazzo workers claim uniformly good results in practice. In this, the thinnest grade of chips is negligible, and the increase in amount from thin to thick is almost constant. Graph *B* (for sample 71) shows a preponderance of chips in the thick grade, while graph *C* is for a sample (No. 27) with a relatively high amount of the thinnest grade. Nearly half the samples showed a distribution as in graph *D*, in which there is a preponderance of the T_3 grade and a distinct drop in the amount of T_4 chips. One aggregate (No. 54) which some terrazzo workmen believe is the cause of poor performance in several installations gave this type of distribution in the tests.

Graphs *E* to *H*, (fig. 3) based on averages, are presented as evidence that the type of distribution shown in graph *D* tends to increase the percentage of voids in the aggregate. Since some samples of this type of distribution have a lower void content than other samples with distributions as shown in graph *A*, it is evident that the amount of voids in the aggregate is not a satisfactory basis for comparison.

[10] The British Standard Specification for Rolled Asphalt (594–1935 and 595–1935).

[11] ASTM Specification for crushed stone for bituminous concrete base and surface courses (D 486–39T).

[12] Report of the Road Research Board for the period ended 31st March 1935; Road Research Bulletin No. 2 "The Shape of Road Aggregate and its Measurement" by A. H. D. Markwick.

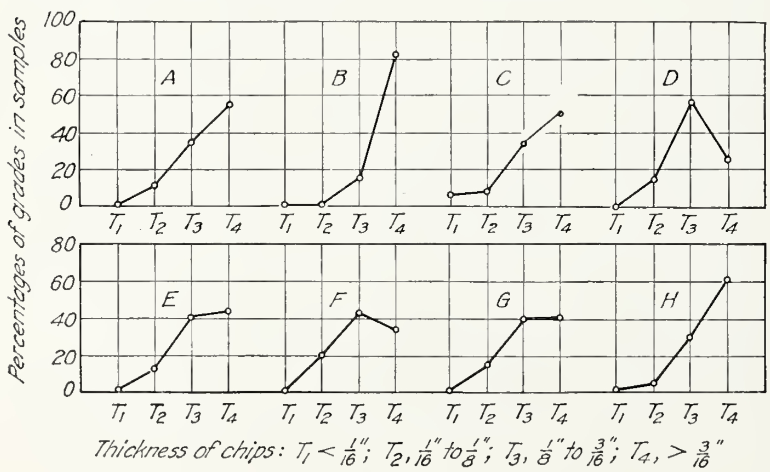

FIGURE 3.—*Thickness-grading curves.*

A, grading of sample 35.
B, grading of sample 71.
C, grading of sample 27.
D, grading of sample 14.
E, average grading of 48 samples.
F, average grading of samples having voids over 43 percent.
G, average grading of samples having voids over 42 percent.
H, average grading of samples having voids less than 39 percent.

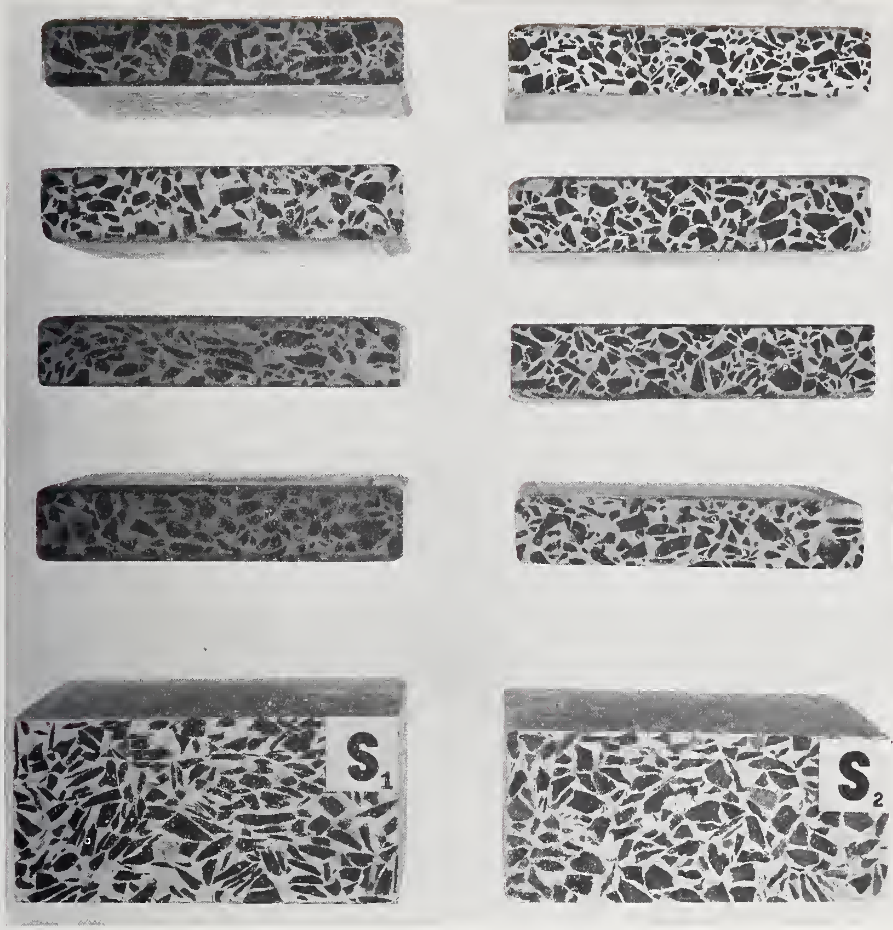

FIGURE 4.—*Cross sections of terrazzo slabs, illustrating the tendency of flat or elongated chips to assume horizontal positions.*

In order to gain some idea of how flat or elongated particles arrange themselves in terrazzo mixtures, made and placed as in actual installations, several samples were obtained from the National Terrazzo and Mosaic Association. These were made in large slabs by experienced workmen and then sawed into smaller slabs. Eight of these are shown in figure 4. A few thicker slabs were made in the laboratory and cut in sections. Slabs *S–1* and *S–2* in figure 4 were selected from the latter group to illustrate the orientation of aggregates having marked elongation. All these were made in the position shown, i. e., the top faces were rolled. It appears from these that long or flat particles are more often turned with their greatest dimensions parallel to the rolled surface. A count of the particles showing elongation in *S–1* and *S–2* was made, in which the particles with inclination less than 45 degrees to the top surface of the slab were recorded as horizontal and all others as vertical. For *S–1*, 70 percent and for *S–2*, 72 percent of the elongated particles were rated as horizontal. The tendency for elongated fragments to assume horizontal positions in bituminous concrete has been pointed out by Lonsdale and Markwick (see footnote 9).

Flat particles arranged mainly horizontal in terrazzo mixtures may interfere with the removal of excess cement paste in the rolling process, thus causing the finished product to be too rich in cement. The failures reported resulted from cracking and indicate that excessive shrinkage occurred. Variations in shrinkage, due to richness of the mix, have been referred

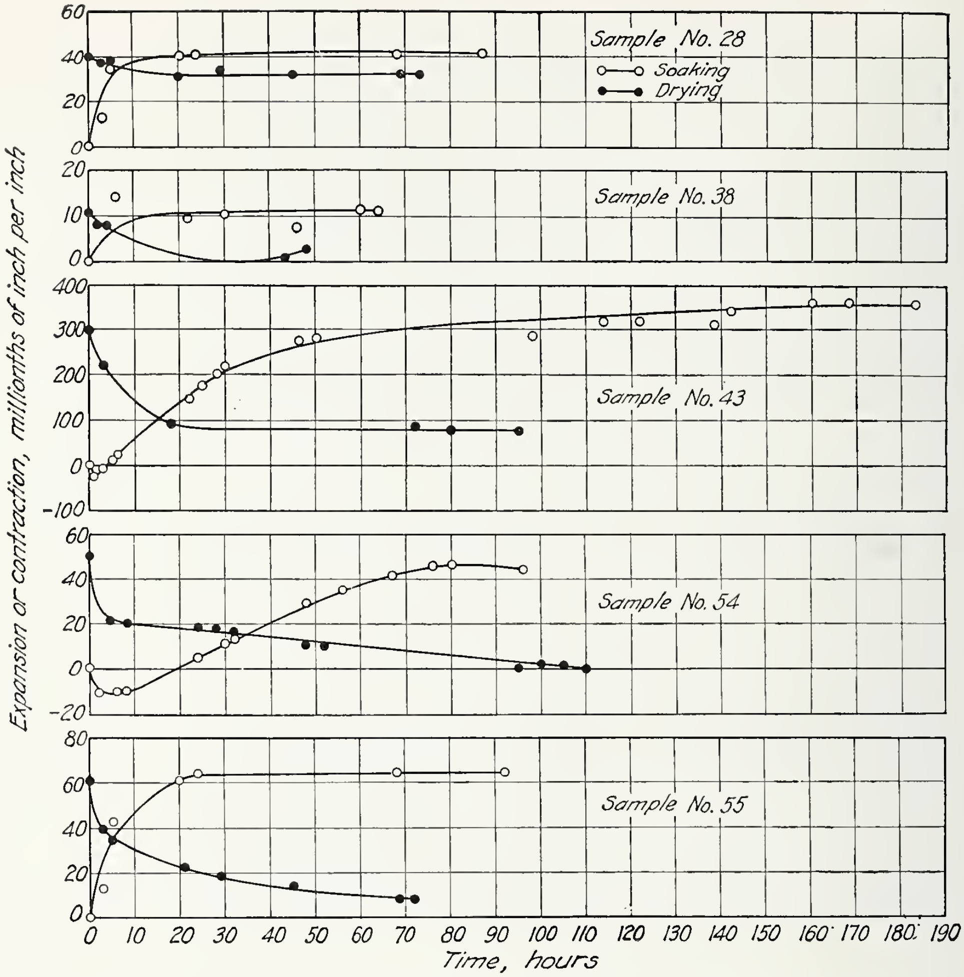

Figure 5.—*Curves for four calcites and a serpentine, showing expansion of samples while soaking in water and contraction while drying.*

to in section IV–6. Further studies on the effect of flat and elongated chips in causing richer mixtures and increasing the shrinkage might prove to be of value.

Since there is evidence that thin chips are objectionable, each producer was asked to supply information on the types of crushing and grading equipment used in his plant. This information is given in table 1. Comparisons of various aggregates obtained by similar crushing methods and also comparisons between similar products obtained with different types of crushers have been made. It was concluded that the shape of particles is influenced more by certain characteristics of the rock than by the type of crusher. Studies have been made at the United States Bureau of Mines [13] on the amounts of flakes obtained by two types of crushers, and the conclusion was that rolls produce more flakiness than ball mills. Although the sizes of crushed material studied were considerably smaller than terrazzo chips, the conclusion might justify further studies on the shapes of particles obtained by crushing certain materials with various types of crushers.

[13] Will H. Cohgill, O. W. Holmes, and A. B. Cambell, Determination of Flakiness of Ores, U. S. Bureau of Mines Reports of Investigations 2899, 4895 (October 1928).

8. Dimensional Changes

(a) *Moisture Effects*

The results of linear expansion and contraction measurements made while specimens were soaking and while drying are shown in figure 5 for five samples. For all of these, except sample 43, the changes were small. Contractions during the drying period were usually somewhat less than the expansions during the soaking. This probably was due to the fact that the specimens were oven-dried at 105° C for the original measurement (before soaking), whereas the final drying was at room temperature (73° ± 2° F). Sample 38 showed the least changes, and these were about equivalent to those that would result from a 2-degree temperature change. Sample 43 expanded very much more than any other sample tested, and the total expansion probably was equivalent to that which would result from a 70-degree change in temperature. The expansion continued over a period of about 6 days, and 70 percent of the total occurred during the first 30 hr. The contraction was more rapid than the expansion, and most of it occurred in 1 day.

Expansions or contractions of a few thousandths of 1 percent, as found for four of the five samples tested, probably have no practical significance. The comparatively large changes found for aggregate 43 (0.03 to 0.04 percent) might be regarded at least as a contributory cause of cracking. When dry chips are incorporated in a mixture, they will absorb water, and expansions will occur over a period of several hours. Some of the expansion will evidently take place after the cement has undergone the initial stages of hardening. If the mixture is properly cured, one may expect the aggregate to remain in an expanded condition for several days. Shrinkage of the aggregate will probably not begin for a few days after sprinkling of the surface has been discontinued. Thereafter, shrinkage of the aggregate will occur simultaneously with shrinkage of the cement paste.

Several small slabs of terrazzo, cut transversely, have been examined to determine if the effects of shrinkage of the aggregate and cement paste were in evidence. Very few instances of separation of aggregate and paste were noted except where rather long cracks occurred. Few such cracks were noted in the small slabs, and in these the cracks sometimes followed the boundaries of chips, and other times, passed through the chips. One sample of terrazzo taken from a monolithic floor showed a network of cracks, and the greatest length of uncracked surface observed was about 8 in. This seems to indicate that shrinkage in terrazzo tends to draw the material in small sections toward the centers of the sections, causing tensile stresses between these centers, which may exceed the tensile strength of the aggregate or cement paste.

All the samples examined showed frequent air pockets which were roughly spherical in shape and varying in diameter from 0.004 to 0.25 in. In several samples there were also numerous voids resembling short cracks in the cement paste. The average length of these was about 0.2 in., and the width varied from 0.004 to 0.02 in. The peculiar shapes of these voids indicate that they were neither air pockets nor cracks, and if they resulted from shrinkage, they were probably formed before the mixture had hardened.

(b) *Temperature Effects.*

Three determinations of thermal expansion were made on sample 54, the aggregate which is claimed to give trouble in terrazzo installations. For each determination the specimens were cut in different directions to give the expansion in three directions at right angles to each other. The expansion curves in figure 6 show that the expansion rates in the directions measured differ considerably and vary for different temperature ranges. All show hysteresis effects and inflection points on the heating curves between 0° and 11° C. The highest coefficient of expansion (0.0000087) was indicated for direction A in cooling the specimen from 60° to 0° C. and negative expansion was found for the direction C in heating the specimen from 7° to 20° C. No inflection points occurred on the cooling

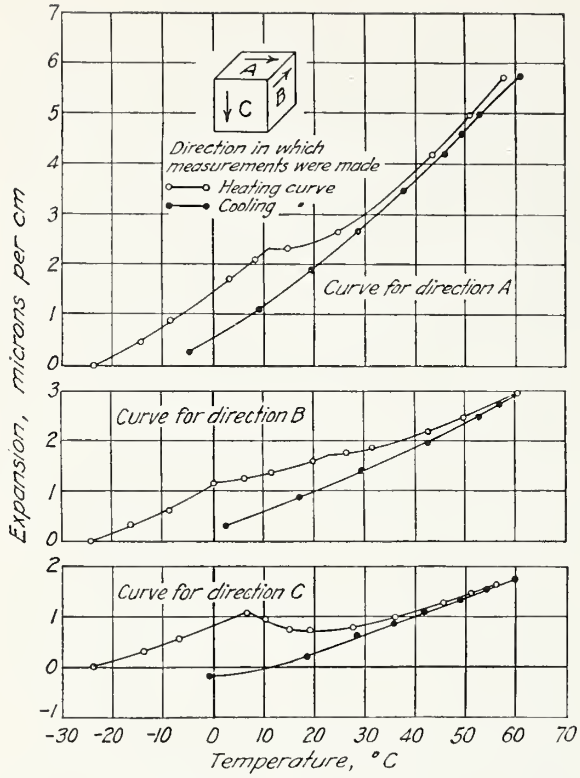

FIGURE 6.—*Thermal-expansion curves for a calcite* (sample 54) *for three directions at right angles to each other*

curves, and the expansion rates gradually decreased as the temperatures were lowered.

The sample was a calcite marble, and calcite crystals are known to have a positive coefficient of expansion in the direction of the principal axis and a negative coefficient perpendicular to that axis. The different expansion values obtained on sample 54 for different directions may possibly have been caused by a preponderance of its crystals being alined in the direction designated *A*. The effects of such differential expansion of an aggregate on the performance of terrazzo have not been determined. Differences between the coefficients of expansion of the aggregate and cement paste have been cited as a cause of disintegration in concrete,[14] and aggregates having marked differences in expansions for different directions have been regarded as detrimental, but there is considerable doubt as to whether such aggregates in terrazzo would cause trouble because of the comparatively small temperature range inside of buildings.

[14] J. C. Pearson. A Concrete Failure Attributed to Aggregate of Low Thermal Coefficient. J. Am. Concrete Inst. 13 No. 1 (September 1941, and Discussion Vol. 16, No. 6 (June 1942).

V. SUMMARY

Seventy-seven samples of terrazzo aggregate were supplied by 24 producers from deposits in 12 States and 1 foreign country. The samples were classified as to mineral composition, and descriptive terms for color, texture, and structure are given. The color terms were derived by the method recommended by the Inter-Society Color Council. These designations often differ from the trade color designations, so the latter are also stated. The tests for comparative data on the rock in its original condition included wear resistance, absorption, bulk specific gravity, and toughness. Tests on No. 2 chips were made to determine the dust content and percentage of voids in the aggregate in the "loose" and "vibrated" states. Certain aggregate samples in the series, including some which have been reported to give unsatisfactory results in terrazzo mixtures, have been subjected to additional tests, such as thermal and moisture expansion.

The abrasive-resistance values (H_a) for the samples range from 8.9 to 112.2 and average 30. Aggregates having H_a values of 18 or higher are considered to be suitable for the most severe conditions of foot traffic.

The bulk specific gravity values range from 2.20 to 2.98, corresponding to weights of 137 to 186 lb/ft^3 of the original rock, respectively. Unit weights of No. 2 aggregate (not compacted) have a range from 82 to 105 lb/ft^3.

Absorption values range from 0.03 to 7.43 percent and average 0.67 percent.

Toughness values (impact resistance) range from 3 to 24. Aggregates having low toughness values show a tendency to abrade and form dust in the shipping containers.

The dust content of the samples varied from 0.09 to 2.08 percent and averaged 0.57 percent.

The average amount of voids in No. 2 chips, not compacted in the measure, was 44.7 percent and when compacted, 41.2 percent. The range for all the samples when compacted was from 36.5 to 50.1 percent. Tests on a few 1:1 mixtures of No. 1 and No. 2 chips gave void contents about 2 percent lower than for No. 2 chips alone. For most aggregates the commonly used proportions (1 part of cement to 2 parts of aggregate) provide considerably more cement paste than is required to fill the voids in the aggregate.

The shapes of chips made from different rocks vary considerably. Some varieties yield fragments approximating spheres, whereas others yield a large portion of flat chips. Flat particles near the surface of terrazzo mixtures are usually turned to a horizontal position during the rolling process and probably interfere with the removal of excess cement paste from the mixture. A test was devised to grade the various samples of No. 2 aggregate into four parts, based on the least diameter of particles. A comparison of the graphs illustrating the distribution of thickness grades in various aggregates shows marked differences in the shapes of these curves for different aggregates. Four varieties of chips which have been rated high in performance by terrazzo workmen, show a fairly uniform increase in amounts from thin to thick particles. Two aggregates reported to give trouble showed large decreases in the amounts of thickest particles from that in the next thinner grade.

Five samples tested for moisture expansion showed a large range in values. One sample expanded nearly 0.04 percent while soaking, an amount about equal to that of a 70° C increase in temperature. None of the others expanded more than that which would result from a 12° C increase in temperature. Contractions of the material while drying were approximately the same as the expansions while soaking.

One sample tested for thermal expansion in three directions at right angles to each other indicated that the material expands at different rates in these directions and that the rates are variable over different temperature ranges. In one direction the specimen contracted as the temperature increased from 7° to 20° C and expanded at higher temperatures. Contractions caused by temperature drops are probably not sufficient to account for the cracking of terrazzo.

The authors express their appreciation to the producers for their cooperation in supplying samples, to D. B. Judd in determining the proper color designations; and to Herbert Insley for microscopic studies in connection with classifying the materials.

WASHINGTON, December 14, 1942.

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[Continued from cover page II]

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