U.S. Geological survey.
Reports. Open file series.

U. S. Geological survey.
Reports Open file series. Translations 1 to 5 (articles on engineering geology) by Mrs. Severine Britt.

Translation No. 5

Building Stones

TESTS AND RESEARCHES ON BUILDING STONES

L'Hermite, M. R., and Feret, L., Essais et recherches sur les pierres de taille: Compte Rendu des Recherches effectuées en 1943, pp. 40-62. Laboratoire du Batiment et des Travaux Publics, Paris.

Translation by Mrs. Severine Britt, U. S. Geological Survey, 1947._/

_/ Published by permission of the Director, U. S. Geological Survey, and of the original authors.

Introduction

In 1941, the "Association Française de Normalisation" (French Association of Standardization) decided to create a Commission for the purpose of writing out a standard for building stones. When this Commission met under the chairmanship of Mr. Pol Abraham, Architect, they realized how far behind was our precise technical knowledge of this kind of material, and found the necessity of determining exactly the testing and acceptance methods. They expressed the wish that a careful study of the subject be entrusted to a specialized laboratory. This wish was received by the Ministry of Production, which, after an agreement with the competent organizing committees, entrusted our laboratory with this work. The main object was to establish the difficulty of stone-cutting in order to permit a classification of the stones according to the difficulty met when working them up into shape, to refer the other technical properties of the stones to this property, and finally to see what relation exists between the figures obtained.

To this end nine stones were chosen by the Commission, from the hardest to the softest: Hauteville, Comblanchien, spotted Larrys, yellow Massangis rock, Euville rock, fine-grained Lavoux, soft Maximin rock, "banc royal" Mery, and "banc royal" Billy. Each type of stone included three large blocks of 0.75 by 0.75 by 0.5 meters to be dressed by hand by specialized workmen, the difficulty of stone-cutting being determined by the time spent for the dressing and preparation of the surfaces. After this operation, detail of which will be given later, we had an important quantity of material which we were to use to the best advantage. I thought that it would be interesting to determine on each one the maximum of physical, chemical and mechanical tests in order not only to be able to compare them in precise conditions, but also to set up each sample as a standard intended for future studies. In other words, each element in the mentioned list must, in my mind, be able to serve in the future as reference to which we will compare the other kinds of calcareous stones used for building. As all the available material was not used, we were able to keep some as a reserve in case later comparisons would be necessary. To this end, we decided to make the following tests:

Physical and chemical tests of identification.--Chemical analysis, and micrography, thermal expansion, density, state of surface.

Mechanical tests.--Strain curve for compression, elasticity, and plasticity; resistance to compression on cubes of 0.08 (standard) and of 0.50 meter; comparison between resistance in dry and in wet conditions; between the resistance of the stone parallel to bedding and perpendicular to bedding; bending strength wherefrom we get the tensile strength (parallel to bedding and perpendicular to bedding); and resistance to wear following various methods (City of Paris and Highway Department); and difficulty of cutting (manual test).

Hydraulic tests.--Porosity, permeability, frost action; perfecting a capillarity test to determine the speed of water rising into the stone; and swelling by water saturation.

M. R. L'Hermite

Report of Mr. Feret

The study was made on the nine stones sent to the Laboratories at the request of the "Comite d'Organisation du Batiment et des Travaux Publics" (Building and Public Works Organizing Committee) and the "Comite d'Organisation des Produits de Carriere et de Dragage" (Quarry and Dredging Products Organizing Committee).

These samples constituted a series of decreasing hardness so that a stone corresponded to each of the stones listed in the old Architects Series or building code.

Stone origins

Stone	Operator
1. Hauteville (Ain)	Guinet Quarries
2. Comblanchien (Cote d'Or)	Quarries of Societe Française de Comblanchien
3. Larrys, spotted (Yonne) commune of Cry)	Derville Quarries
4. Massangis, yellow rock (Yonne)	Pagani Quarries
5. Euville rock (Meuse)	Fevre Quarries
6. Lavoux, fine (Vienne)	Givet-Pommer Quarries
7. Saint-Maximin, soft rock (Oise)	Ouachee and Corpechot
8. Mery, "banc royal" (Seine and Oise)	Fevre
9. Billy, "banc royal" (Aisne)	Cullot

The above list shows that very diverse regions of France are represented; however, these samples have but a small number of geologic origins. The three softest: Saint Maximin, Mery and Billy belong to the Lutecian stage of Eocene age. Consequently they are of more recent formation than the others. All three are of cream or yellowish color, and have a sandy homogeneous appearance; the bedding planes of Saint Maximin are, however, much more pronounced than the other two.

The harder stones date from the Jurassic and most of them come from Burgundy where numerous ledges exist. Among these is the Comblanchien bed at the Bathonian level, whose outcrop coincides with the location of the well-known vineyards. These stones are generally compact, and of various textures and colors giving decorative effects.

Hauteville is crossed by suture veins. Comblanchien is mottled with crystalline dots and cut by red veins. Spotted Larrys is, as its name implies, mottled with grayish dots of glassy appearance. These three stones are whitish, very fine-grained, and will take a polish.

Massangis is muddy-yellow, fine-grained, and of heterogeneous texture with nodules of irregular dimensions and shapes, and of same color. The whitish Lorrainese stone of Euville is remarkable for the dimension of the fossils which compose it and which are bound together by a natural crystalline cement of saccharoid glitter. This stone dates from the Corallan Jurassic. The Poitou stone "Lavoux" belongs to the Bajocian. It is of oolitic structure, fine-grained, and white with a few gray spots.

Chemical Analysis

	% Loss on ignition CO_2	% Loss on ignition Other	SiO_2 %	$\%Al_2O_3 + Fe_2O_3$	CaO %	MgO %	SO_3 %	$\%CaCO_3$ as referred to CO_2
Hauteville	42.6	0.6	0.8	0.2	55.0	0.3	0.1	97
Comblanchien	42.7	0.1	0.7	0.4	55.3	0.4	0.1	97
Larrys, spotted	42.0	1.4	0.5	0.2	55.9	0.2	0.2	95
Massangis, yellow rock	42.5	0	0.5	1.1	55.5	0.3	0.1	97
Euville rock	41.0	1.0	1.4	0.8	55.0	0.5	trace	90
Lavoux, fine	43.0	0.5	0.5	0.1	55.0	0.4	trace	98
Saint-Maximin, soft rock	33.9	1.5	17.3	0.1	46.3	0.4	0.2	82
Mery, royal white	34.4	1.7	14.5	1.5	46.7	0.5	0.1	78
Billy	37.6	0.9	5.0	1.2	54.3	0.6	trace	86

Carbon dioxide was determined by gravimetric analysis with the Fleurent apparatus. The rest of the analysis was made following the usual method for silico-calcareous materials. It was not deemed necessary to determine separately the iron oxide on account of its small percentage.

From an experimental point of view, stone testing may be divided into several categories. On one hand, the standard tests, or at least those in process of standardization, for the Afnor has not yet ratified the project presently under study; on the other hand, the tests which are not usually applied to stones but are used for other materials; and finally, the tests bearing on characteristics which are scarcely or never observed and which have necessitated the creation or adaptation of special apparatus.

Stone testing can also be classified as mechanical and physical tests.

For the presentation of testing methods, the standard tests will be described first, then among the others the mechanical and the physical tests.

Standard tests are: capillarity of dry stone parallel to bedding, porosity, apparent density, freezing, resistance to crushing of dry stone parallel to bedding, wear, and hardness or difficulty of stone-cutting.

Special mechanical tests made: wearing tests with different machines, crushing and bending strength of the dry and wet stone parallel and perpendicular to bedding, determination of elasticity of stone under compression and bending in dry and wet conditions.

Physical tests refer to contraction on drying, thermal expansion, and permeability to water.

Prior to each measurement, each test-piece is dried to constant weight in the drying oven at forty degrees centigrade.

Apparent density and porosity.--The apparent density (in kilograms per m^3) is determined on standard test specimens by the ratio of the weight (estimated to a gram) to the apparent volume of the test specimens. Porosity: normal test specimen (dried)_/ shall be measured and weighed with a balance sensitive

_/ The volume of irregular blocks which cannot be sawed will be determined by means of a hydrostatic balance.

to a decigram.

Vacuum will be created with a hydraulic suction pump one-fourth hour under reduced pressure of 25 mm of mercury, then water is introduced slowly so that the test specimen remaining under constant reduced pressure is not thoroughly immersed before one-fourth hour.

After the air extraction has ceased, the atmospheric pressure is brought back and the test specimens are kept immersed for twenty-four hours, then wiped off and weighed while saturated with water.

The volume of pores is determined by the volume of water corresponding to the difference in weight of the test-piece before and after absorption.

Porosity (in per cent) is given by the ratio of the pore volume to the total volume of the test specimen._/

_/ It is a question here of the absolute porosity and not of the coefficient of absorption in weight: ratio of the weight of water absorbed to the weight of dry test specimen.

The paragraphs referring to both of these tests have been deliberately brought together as they are conducted pari passu. The standard is not very explicit about the method of determining the volume of the test specimen. Here is the process adopted:

The test of normal porosity is made first by weighing the test-piece with a Roberval balance, sensitive to one gram; a greater precision is useless and brings only a variation in the third decimal. The cube being weighed immediately after saturation, the apparent volume is established exactly only if the pores of the stones are closed. For this purpose, paraffin or vaseline are ordinarily used, but the weight and volume of these substances must then be taken into account.

The determination of the volume by the saturation method will be in accordance with the Archimedean principle, as there is here no influence of exterior agents. Determination of the volume by a sliding caliper gauge is more apt to introduce errors, because it is difficult to take into account accurately the curves or unevenness of surfaces.

The dry and wet weights and the volume being known, it is easy to compute the porosity and apparent density.

In general there is little difference from one sample to another for these measured values, except in stones with cavities.

	Apparent density	Porosity
Hauteville	2.656	1.00
Comblanchien	2.685	0.24
Larrys	2.548	4.98
Massangis	2.409	10.32
Euville	2.289	14.75
Lavoux	1.932	28.00
Saint-Maximin	1.708	36.33
Mery	1.609	40.12
Billy	1.588	42.58

These are the mean figures for six test-pieces.

Capillarity.--Three standard samples are selected from the same bed: "A" from the upper part, "B" halfway up, and "C" at the base.

Direction of bedding shall be carefully marked near the upper side of each sample.

Samples are dried to constant weight and weighed.

Capillarity, proportional to the weight of water absorbed during a given time, is determined by the coefficient:

$$C = 100\frac{W}{A\ t}$$

where: W = total weight (in grams) of water absorbed from the beginning of immersion;

A = area (in cm^2) of low face of test specimen;

t = total time (in minutes) from the beginning of immersion;

100 = a factor to raise C above unity.

The samples are placed base down, parallel to the bedding, under a glass jar on a screen, and soaked in 5 mm. of water at 15 to 20 degrees centigrade. During the test, the level of water is maintained constant to 5 mm ± 1 mm. After the water has been absorbed to a height of about 35 mm., the sample is thoroughly wiped off and weighed as rapidly as possible. Increase of weight (W) and the time (t) elapsed since the immersion shall be noted. The sample is replaced on the screen and water level reestablished.

The operation is repeated as many times as necessary, the time of each operation being twice as long as for the preceding operation. The last measurement is made when the water is about to reach the top of the sample.

Coefficient C is determined for each measurement and the maximum value of C obtained is given to the sample.

The capillarity is determined by the arithmetical average of coefficients C given respectively to samples A, B, and C.

This test applies naturally to relatively soft stones. The stones with negligible porosity were avoided. This test reveals the homogeneity of the rock, in two manners: (a) during the test, if the stone is uniform the level remains horizontal; if more compact concretions are present the rising water can be seen outlining spots which remain dry or are reached much more slowly; (b) in the difference of value of coefficients C from one sample to another or during the same test.

The capillarity test is made in an atmosphere saturated with water vapor, in this specific case under a glass jar. This precautionary measure is necessary in order to avoid the evaporation of water on the surface, but it places the test in the most unfavorable conditions and permits a more strict classification. In fact, in nature these conditions are seldom realized and the alternation of the elements reduces more or less these effects.

Coefficient C chosen to characterize a sample is the maximum value found during the different measurements made on the sample; the manner of expressing it is also the most unfavorable but it eliminates the influence of obstacles which generally retard rising water: veins, threads, holes, nodes, etc.

The yellow rock of Massangis is the most characteristic. It is composed of very compact concretions, occupying about one-fourth of the volume and bound together by a softer filling of the same color but distinguished by a special grain. These different zones are remarkably shown up in the course of the porosity test. On a sample taken out of water after a rather long immersion, one notices soon after wiping it off, the appearance of spots which dry very rapidly and correspond to these concretions. Their distribution naturally changes all the properties of the stone, and of all the tests this one shows the greatest divergences.

One should not on this account conclude that this stone is less fit than another one to normal uses, for the softest part is itself of an appreciable hardness and the nodules only increase it.

Value of coefficient of capillarity "C" for the different stones:

	Mean of maxima		Maximum of maxima		Minimum of minima	
	Parallel to bed	Perpendicular to bed	Parallel to bed	Perpendicular to bed	Parallel to bed	Perpendicular to bed
Larrys	0.28	0.33	0.32	0.42	0.15	0.16
Massangis	2.33	5.22	3.61	12.14	0.46	0.25
Euville	4.23	3.24	4.65	3.61	2.76	2.55
Lavoux	18.4	19.2	19.2	20.1	15.0	16.1
Saint-Maximin	35.9	40.2	36.1	42.9	29.8	36.9
Mery	27.8	32.0	30.0	37.2	23.2	24.2
Billy	32.3	38.9	41.0	41.9	24.1	29.7

Resistance to compression.--The bedding surfaces of the normal test specimen shall be faced up by grinding so as to make them perfectly smooth and parallel.

The sample is placed between the plates of a hydraulic press, bedding planes parallel to the face of the specimen to which pressure is to be applied, and with a sheet 2 mm thick of dry millboard placed between the sample and the press.

Increasing pressure is applied gradually until the stone ruptures.

The crushing strength (in kg per cm^2) is determined by the ratio of the breaking load to the surface of the face under pressure.

This test is made under the same conditions as for other materials.

It does not lead to very special observations. According to the hardness of the stones, it is observed after crushing that the sample breaks down either in symmetrical frusta of pyramids, or in vertical needle-shaped sections with reticulate horizontal faces.

The range of results may reach great proportions, which is not surprising as one deals with a natural material.

Freezing.--Same operations as for the porosity test. Then:

Submit the test specimen for 4 to 6 hours in a refrigerator at a temperature of -15 degrees to -20 degrees centigrade, remove and immerse for at least four hours in soft water at 15 to 20 degrees centigrade, the volume of which should be five times the volume of the specimen. Repeat the operations of freezing and thawing twenty-five times in succession with intervals of five minutes maximum between the removal from the refrigerator and the soaking in water and vice versa. The specimen will be examined after each removal from the water bath.

The results of freezing are characterized separately for each test specimen, by the absence or the presence of apparent alterations, as well as by their shape, importance, and the number of cycles that preceded them.

The difficulty of interpreting the test lies in this method of estimation. Whereas in the other tests, the results are numerical, in the present case any estimation is purely subjective.

To meet with this difficulty, the laboratories generally make the strength test subsequent to freezing when the state of the sample permits it. One should beware of the fact that the stone is then saturated with water, which considerably reduces its strength. That is why even some apparently undamaged stones fail.

The action of freezing is different according to the stones. For soft stones, it appears in the rounding of the corners, so that the samples finally acquire a more or less spherical form, the radius of which shortens in the course of the test.

The harder stones have a tendency to quarter or to cleave due to the gradual widening of cracks, the separated fragments still remaining hard.

Difficulty of dressing.--The test for difficulty of dressing, which is manual, is only a comparative test. The operations are made simultaneously by three workmen working successively on a test specimen, and for comparison on two other specimens of two stones of a closely related nature, but one being harder and the other softer.

Preparation of test-pieces.--The sample shall be selected at a height of the bed corresponding to its approximate average hardness (dirt and hard heads excluded).

A test-piece shall be cut from each type of stone, in the shape of a right rectangular prism with all faces at right angles and with the following dimensions:

Length	75 cm
Width	75 cm
Height, perpendicular to bedding	50 cm

measured from the bottom of each groove as described hereafter:

Approximate diagonal grooves 4 cm apart and 15 mm deep shall be cut with a chisel or a pick on the 75 by 50 cm faces; the bedding faces being rough-sawed.

The rest of the preparation conforms to the conditions of standard sampling and test specimens.

Conduction of the test.--As the manual test for the determination of the difficulty of dressing can only be comparative and approximate, the operations shall be conducted simultaneously on the test specimen of the stone "B" and on the test specimens of two other stones of a closely related nature, but one, "A", being harder, and the other, "C", softer, chosen for comparison.

One sample of each stone A, B, C shall be used.

a. Very hard, hard or semi-hard limestones. Principle: on three of the 75 by 50 cm faces of the test-pieces which have already been grooved, the following operations shall be performed:

1. Bush-hammer (using the one hundred tooth hammer) the surface between the chiseled grooves;
2. Grind the bush-hammered surfaces.

For this test, three stone-cutters will be chosen who are familiar with the different hardnesses of stones and who have already dressed the three kinds of stones to be tested, or stones of similar nature. The three workmen, using the same tools and ingredients, and working in different rooms / will complete by hand the operations mentioned above on one 75 by 50 cm face of one of the three test-pieces. The dressing time spent by each worker will be noted.

/ In order to avoid a tendency for the workers to wait for each other.

The three workers will be exchanged and each one will perform the operation on a different 75 by 50 cm face of another test-specimen, so that finally each worker will have made the two dressings on one face of each test-specimen.

For each sample A, B, C, will be found the averages of the dressing times spent by the three workers to make the two dressings on each respective test-specimen.

The comparative difficulty of dressing stone B is estimated by the time used to dress specimen B as compared to time spent on A and C.

b. Soft limestones.
Make the same operation as above on the grooved faces, but with only one dressing; redress evenly and finish with a scraper.

The following points influence the character of the test:

1. The dimension of the samples, which are very large stones weighing 600 to 800 kg.
2. The frame of mind of the laborers, who do not necessarily understand what is required from them and think more or less that they are personally subject to checking, and who will react according to their temperament. So two series of tests were made in the laboratories. Moreover, in order to increase the precision of the test, each quarry sent three blocks instead of one as called for in the standard specifications. In the first series, the three workers worked together. It was noted that one of them, older and better trained than the other two, had a tendency to slow down more or less consciously toward the end

of the work, and consequently there was little difference in the results. In the second series which dealt with the three hardest stones, an attempt was made to cope with this situation.

First, as the necessary personnel was not available, one workman did all of his work alone; he must have thought that it was in view of a competition as he worked at an accelerated speed with a detriment to the finish. The two other faces were taken later on by two other workers, both of whom worked on a block of different origin. In this case, the same reflex occurred and although they were working on different rocks, they completed this work at the same time. It is difficult to meet with this state of affairs because the control of the time spent necessarily requires the presence of a timekeeper, and this brings to the worker's mind the memory of useless military duties which makes him take special care not to be through with his work before the others.

But in the present case, as the stones were of closely related hardness, the divergences were not so noticeable as could have been expected, particularly as the time for finishing hard stones is rather uncertain and depends very much upon the peculiarities that may appear on the surface to be dressed. Besides, this test due to its nature is very subjective and will never, under this form, be liable to acquire the exactness of more scientific tests, the difficulty of the problem being to find workmen really qualified and understanding.

In spite of these difficulties, the average dressing times are graded in a satisfactory manner according to the degree of hardness foreseen. This is shown by the following comparisons made by Mr. L'Hermite:

Time of cutting (for 1 m^2)

Hauteville	58 h. 56
Comblanchien	53 h. 26
Larrys	49 h.
Massangis	13 h. 8
Euville	5 h. 21
Lavoux	2 h. 58
Saint-Maximin	1 h. 56
Mery	57 minutes
Billy	55 minutes

Wear.--The test specimens are cut in the shape of a right rectangular prism having bases 6 by 4 cm parallel to the bedding and smoothed by grinding; the height is 10 cm. The rest of the preparation will conform with the standard test-pieces.

Each test-piece is placed bottom down and held by its length and width so that it is guided to a cast-iron grinding wheel. The test-piece is then submitted to grinding by a standard sand_/ which is fed at a rate of 1 lit. per

_/ Standard sand: Grind and sift medium hard Fontainebleau quartzose sandstone or any other natural product of same hardness and rounded shape, passing through a No. 27 screen but entirely withheld by No. 21 screen; fifty per per cent in weight being made up of the sand retained by No. 24 screen. (For the screens, see Afnor standard specifications M 6-1.)

half hour upon the cast-iron grinding disk turning at a speed of 3,300 meters per hour.

At the same time, the load is increased to 250 gr. per cm^2 against the grinding surface.

During the test, hard fragments or exceptionally coarse grains shall be removed with a chisel or by grinding, as their prolonged presence could damage the grinding disc. If this is done, it should be mentioned in the report.

Measure to 1/10 mm the loss of height of the test-piece after about 6,600 meters run of the grinding wheel, the run being evenly divided between each base.

The wear (in cm) is determined by the relation of the loss of height to 10,000 meters of revolution of the disc.

These methods are those used with the Dorry machine of the Laboratoire de l'Ecole des Ponts et Chaussees (Laboratory of the Highway Department School) and the Laboratoire de la Ville de Paris (Laboratory of the City of Paris).

In this apparatus the testing-piece is placed on a horizontal cast-iron disc, rotating at 2,000 revolutions per hour, in which a run of 3,300 meters represents an average radius of 26 cm. During the same test two test-pieces are placed diametrically opposite. The test is run for 4,000 revolutions, during which time the sample is turned over in order to abrade both bases equally.

This test is undesirable for soft stones in that they wear out very fast and the dust thus formed mixes with the standard sand and reduces its abrasive power. The test is influenced by the "abrasivity" of the stone itself, debris of which contributes to alter the results.

This wear test ends the description of the standard tests.

Other wear tests.—Mechanical tests (not standard) made in the Laboratoire de la Ville de Paris (Laboratory of City of Paris) and in the Laboratoire du Batiment et des Travaux Publics (Laboratory of Building and Public Works) are described below.

The Laboratory of the City of Paris uses the Anstett apparatus which has about the same working characteristics but differs in construction.

This apparatus does not use a disc but a cast-iron cylinder along which the supports for the test specimens are placed; a container delivers the standard sand either dry or suspended in the water. This procedure is generally preferred because it eliminates dust. The section of the test specimen is a little larger: 65 by 45 mm (instead of 60 by 40 mm) but the load per cm^2 is the same, which allows comparison of the tests. These last dimensions are also used with the machine of the Laboratory of Building and Public Works, which is also an Anstett machine, but differs from the others as regards the conditions of testing. With this machine, the test specimen is moved about on the abrasive which consists of a dry No. 5 carborundum canvas, which is changed after a run of 125 meters, the complete test consisting of a run of 250 meters. The speed of 30 meters per minute or 1,800 meters per hour, is a little more than one-half of the preceding test of 3,300 meters. A dust-exhauster, integral with the test specimen holder, exhausts the dust as soon as it is produced. But in spite of this improvement, it is difficult to prevent the abrasive from being clogged by the soft stones.

With these three apparatus, rather important divergences are noted between the different test specimens of the same stone. For example:

Apparatus P and C (Ponts et Chaussees),	"banc royal" Billy:	26.05 cm,
		71.96 cm,
		44.0 cm.
Ville de Pâris, wet test:	"banc royal" Mery:	82.2 cm,
		168.4 cm,
		205.8 cm.
Apparatus LBTP (Laboratoire du Batiment et des Travaux Publics)	"banc royal" Billy:	16.8 cm,
		21.0 cm,
		15.8 cm.

These divergences are particularly noticeable with soft stones. Also for soft stones, the tests have mainly an experimental classification value, these stones being seldom used where they would be subjected to wearing. Generally, only the hardest stones are submitted to these tests, as they are generally more uniform. For a better comparison of the results all the numbers in Table II were reduced to a run of 10,000 meters. The rough results, as a whole, are given in Table I together with the results of porosity and apparent density.

Table I

Names	Apparent Density	Porosity Per Cent	Wear: V.P. (10,000 m) (City of Paris) Dry	V.P. (10,000 m) (City of Paris) Wet	P.C. (6,560 m) (Highway Dept.) Dry	L.B.T.P. (250 m) Bldg.&Pub.Works Dry
1 Hauteville	2.654	0.94	12.3	33.2	1.61	0.70
	2.654	0.94	11.7	29.4	1.40	0.95
	2.660	1.14	16.3	33	1.40	0.80
	2.656	1.00	13.43	31.87	1.47	0.81
2 Comblanchien	2.698	0.37	9.6	26.5	1.31	0.75
	2.674	0.18	13.4	25.9	1.29	0.65
	2.684	0.18	12.9	28.9	1.23	0.65
	2.685	0.24	11.97	27.1	1.28	0.68
3 Larrys, spotted	2.549	5.04	16.3	41.6	1.90	1.3
	2.559	4.69	19.3	40.8	1.86	1.25
	2.536	5.21	19.1	41.5	1.82	1.15
	2.548	4.98	18.23	41.3	1.86	1.23
4 Massangis yellow rock	2.416 2.293	10.00 15.02		61	3.35	2.6
	2.433 2.442	9.62 9.26		54.7	3.21	2.8
	2.444 2.456	8.98 8.50		62	2.89	2.5
	2.414	10.27		59.23	3.15	2.63
5 Euville rock	2.262 2.284	15.21 13.51		92.3	7.28	12.90
	2.240 2.262	15.71 14.36		114.8	8.60	14.66
	2.246 2.262	15.54 14.19		121.2	5.15	12.69
	2.259	14.75		109.43	7.01	13.41
6 Lavoux, fine	1.940 1.941	27.92 27.69		291.5	12.88	90.63
	1.934 1.933	27.66 27.99		535.3	4.33	95.68
	1.918 1.928	28.43 28.30		455.8	5.71	102.33
	1.932	27.99		427.53	7.64	96.21
7 Saint-Maximin soft rock	1.713 1.700	36.25 36.74		791.2	5.98	299.28
	1.720 1.699	35.99 36.71		903.4	8.21	277.33
	1.709 1.707	36.41 36.20		791.2	8.65	260
	1.708	36.38		828.6	7.613	278.87
8 Mery "banc royal"	1.572 1.642	41.48 38.84		852.1	9.92	556.40
	1.597 1.621	41.11 39.38		1,693.9	9.48	480.48
	1.573 1.648	41.23 38.68		2,057.6	8.12	577.20
	1,668	40.12		1,534.3	9.17	538.02
9 Billy "banc royal"	1.580 1.600	41.17 40.40		1,273.8	5.34	194.69
	1.555 1.641	42.52 50.30		1,590	3.45	173.89
	1.538 1.615	41.17 39.94		1,608.5	4.09	196.35
	1.588	42.58		1,490.76	4.293	188.31

Non-standard crushing tests.--The standard tests are made on cubic test specimens, 8 cm on the edge, dried to a constant weight at forty degrees and crushed parallel to the bedding. The change of one of these conditions leads to notable variations in the results. This is why tests were also made on cubes 50 cm to a side, or 30 cm for the hardest stones, in order not to risk going beyond the power of the 2,000 ton jack of the laboratory. However, this measure was useless as the resistance on large blocks is much smaller than the resistance on standard cubes. There are several explanations for this: difficulty of obtaining a sufficient smoothness of the bearing surfaces even though a cement coating has been applied on each contact face to avoid this inconvenience; greater influence of the peculiarities of the stone; veins, threads, cavities, etc., which are so much more numerous in the larger stones and which could cause a break in the continuity. For instance, the Comblanchien broke at 665 kg whereas its normal resistance is 1,296 kg. The cube was crossed halfway up by a red vein along which the breaking started, the acicular fragments resulting generally from the splitting in the middle of the hard stones. The Hauteville was crossed by several sutures (joints) which gave a similar result (610 as against 1,265). As a last explanation, one can also object to the impossibility of drying such a large mass, especially the soft stones. The ends of prisms resulting from the bending test were used to determine the crushing strength of each stone parallel and perpendicular to bedding, either dry, or saturated as much as possible. The section of the test specimens was 50 cm^2. The saturation was obtained in the same way as for the determination of porosity.

Flexure test.--The bending test for the determination of either elasticity or strength was made on a prism 7 by 7 by 26 cm, similar to those used for concrete.

A direct-loading apparatus was used in preference to the manometer lever which is not so sensitive to small stresses (fig. 1). The deformation under stress was measured with the Huggenberger extensometer and the coefficient of elasticity computed. Two apparatus were used, one on the face under compression, the other on the face under tension. This was based upon the principle that according to the coefficient of amplification of each apparatus, 1 mm of graduation corresponds to a variation of 10 μ per meter. Measurements were made parallel and perpendicular to bedding on both dry and wet stones for testing elasticity as well as resistance under bending to the point of rupture.

For elasticity under compression the Huggenberger extensometer was replaced by the Coyne vibrating cord apparatus mounted on stone cylinders 9 cm diameter by 20 cm high; two parallel grooves diametrically opposite each other are made in the ends of the cylinders, in which are cemented metallic plugs connected by sound-frequency steel cords.

The test consists of measuring the deformation by the change of the sound of the cords. For this, an electromagnet is placed near each cord, which serves simultaneously as an exciter and recorder; the sound is received by a low-frequency amplifier, which can also receive, in series, the vibrations of a cord adjustable by means of a micrometer screw; the measurement is made by adjusting it until the two sounds are superposed without pulsation. Precision of 10 microns per meter, or better, can be obtained.

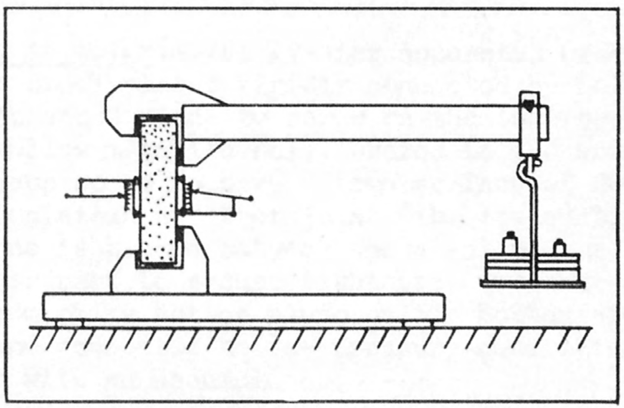


FIG. 1.- DIAGRAM OF THE APPARATUS USED FOR THE FLEXURE TEST.

For hard stone, the load is gradually increased by 20 kg, using a fly-wheel press (presse a volant), the only one able to maintain a constant pressure during the time of reading, the pressure being recorded by a manometric diaphragm. For soft stones, a weight-lever was used, the ratio of which is 1:10, giving a force of three tons. The load is gradually increased by 10 kg, but for some stones by 5 kg. The test was first made on a wet stone; then the test-piece was dried in the oven at 45 degrees centigrade and the test made again in dry condition.

The elasticity in wet condition is greater than in dry condition; for most of the stones, there is little variety in the results from one test-piece to the other.

Shrinkage on drying.--The test with the Coyne cords gives a supplementary result on the shrinkage on drying. As test-pieces were studied on which cords were stretched to a known frequency, the only operation necessary after drying and cooling was another measurement to estimate the shrinkage of the test-specimen. The results obtained are rather confused and hardly correspond to any other property of the stones. Also, in this case, considerable divergences are noted from one sample to another.

Permeability to water.--The Tissier apparatus used consists of:

a. Two steel plates rigidly connected by bolted rods;

b. A threaded piece to screw on the test specimen;

c. A hollow metallic bell, brazed to the water delivery pipe, shaped like a spherical cup so as to have a free surface of 20 cm^2; a circular groove is cut inside to maintain a rubber joint (the tested blocks were 15 cm by 15 cm by 5 cm). Each one is placed between the steel plates; a small rubber disc is placed in the upper part to secure tightness, and another in the lower part to keep the block from being out of plumb on the bottom steel plate; the specimen is screwed home and connected to the pressure-generating apparatus, in this case a compressor with an accumulator.

A funnel is placed under the apparatus to receive all the water flowing through the block which finally will be collected in a graduated test tube.

The purpose is to allow the reading of the outflow volume at any time without interrupting the test; and, on the other hand, if several apparatus are placed near each other, the difference of permeability of materials submitted to the same water pressure will be seen at a glance.

The test was made on two samples of each stone. In general, the results were rather accordant. Depending on the porosity, a pressure of 2 kg or 5 kg was applied and measurements from ten minutes to twenty-four hours were made and repeated several times. The delivery, at first relatively high, decreases rather rapidly and starts to become steady after a more or less long period of time or of outflow. At this stage, the flow is about one-fourth of that at the beginning of the test. This is due probably to clogging, coming from the solution of lime carbonate and also, certainly, from particles carried by water. When removing the test-piece, a darker circle is seen corresponding to the interior diameter of the rubber disc. (The time was not available to pursue the test, but it is likely that a nearly complete impermeability could be reached under constant pressure.)

Thermal expansion.--The test for thermal expansion between 15°C and 100°C was made in the Laboratoire d'essai du Conservatoire des Arts et Metiers (Testing Laboratory of Arts and Crafts School) _/ by means of the modified

_/ Sur la dilatomètric dans un intervalle de -50°á + 150° (On dilatometry in the interval -50°C to + 150°C) by P. Dubois and R. Walden, Chemie et Industrie, vol 47, Mai 1942, p. 540.

Chevenard dilatometer.

A diagram of the apparatus is shown below (fig. 2). For all the stones, the diagram of expansion is rectilinear except for the Euville stone where it is somewhat inflected.

Dilatometric study of different stones.--Characters of samples: A section of 6 by 6 by 135 mm was cut in each one of the different stones.

Method.--Each of these samples was studied with the optically registering Chevenard differential dilatometer, modified by the Testing Laboratory of the Arts and Crafts School. The oven was provided with an automatic rheostat allowing a regular increase of atmospheric temperature to 200°C in 4 hours.

Results.--A full-scale copy of the curves obtained is attached with a note on the calculation of the coefficient of expansion. (Translator's note: These curves did not appear in the original publication. Coefficients of thermal expansion are shown in fig. 19.)

With $n = \frac{200}{135}$ $e = 23.3 \times 10^{-6}$ $s = 0.54 \times 10^{-6}$ $\frac{Kx}{Ky} = 0.464$

the following values were found:

Sample references		15° at 100 x 10^{-6}
BR	Billy "banc royal"	6.8
MR	Mery "banc royal"	3.3
SM	Saint-Maximin soft rock	6.6
LF	Lavoux fine	3.1
ER	Euville rock	13.3
MS	Massangis yellow rock	6.4
LM	Larrys spotted	1.5
CB	Comblanchien	1.5
HR	Hauteville	1.4

This is the series of tests that were made. Some will doubt the interest of these tests and will object that man did not wait for laboratories to learn how to erect buildings which defy time. The author believes that the great age of building-stone use is the reason why the methods of using it were not subject to greater development. A better knowledge of the material would be most advantageous. It is that which has meant success for the more recent methods of construction, which owe their development to the simultaneous improvement of techniques which could also be applied to stones.

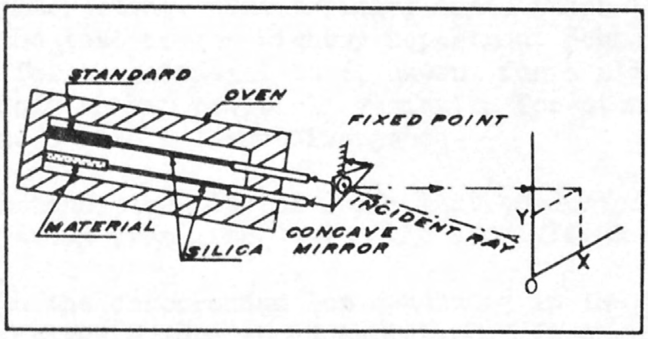


FIG. 2.- DIAGRAM OF THE CHEVENARD DILATOMETER.

As Mr. Vitale said in his lecture of April 21, 1941, "Setting the material in its right place makes the building sound, and is also the best ornamentation."

To set the material in its right place means also to turn it to the best account and this has always been the aim of the men interested in construction.

Interpretation and conclusions by Mr. L'Hermite

Following the report on Mr. Feret's experiments, general conclusions are given by means of diagrams.

Difficulty of stone cutting: In Table II which is a comprehensive summary of some properties, column 3 shows the time of cutting converted to a standard sample of 1 m^2. On the accompanying graph (fig. 3) the cutting time is represented by the logarithmic abscissae while the diverse properties to be studied are on the ordinates. Both density and porosity will first be carried on normal coordinates; the coefficient of wear given by the different methods will be shown on logarithmic ordinates.

It will be seen that the coefficient of wear decreases when the time of cutting increases, which is not surprising; but the comparison of the different methods is more interesting. The official test, which the Afnor wants to standardize, is the test of the Highway Department School. It gives a rather linear variation for the stones 1 to 5, except for a slight deviation for stone 2, but it gives only an imperceptible variation for stones 5 to 8, and rises suddenly for stone 9 with a large divergence.

On the other hand, the City of Paris test conducted in wet condition gives a continuous variation from 1 to 9 with the same slight deviation for stone 2.

The test with the carborundum lap conducted in the Laboratory of Building and Public Works, gives a more rapid variation. It is seen that the results of wear obtained by the method VP (City of Paris) gives the same classification of stones as the test for the difficulty of cutting, except however that there is an anomaly between stones 1 and 2. This anomaly is said to have come from an irregularity in the sample of Hauteville stone which had been provided for the test. Other samples which are to be sent will show if this statement is correct. It remains true that the test for wear, like that for difficulty of cutting, will not permit a precise differentiation between no. 1 and no. 2 of the series, as a simple variation in the quality of a specific sample may reverse the classification.

The Highway Department test, on the other hand, gives a precise classification for the numbers 1 to 5 only, as beyond this the strength variation becomes imperceptible. There is here a very interesting correlation which leads us to decide in favor of the VP test, which can give us definite information on the difficulty of cutting to be expected for a specific stone. The following empiric formula valid to ± ten per cent can be written from the curve obtained; let:

u = the VP coefficient of wear, and
T = the time of cutting in hours

$$\log. u = 0.11 (\log. T - 5.4)^2.$$

Table II

No.	Name	Cutting time per m^2	Wear: City of Paris Wet	Wear: City of Paris Dry	Wear: Highway Dept.	Wear: Bldg. and Pub. Works	Apparent Density	Porosity Per Cent	Per Cent of $CaCO^3$	Capillarity: Paral. to bed	Capillarity: Perp. to bed	Permeability in grams per hr.
1	Hauteville	58 h 56	31.87	13.43	22.4	32.4	2.656	1	97			0
2	Comblanchien	53 h 26	27.1	11.97	19.4	27.2	2.685	0.24	97			0
3	Larrys spotted	49 h	41.3	18.23	28.3	49.2	2.548	4.98	95	0.28	0.33	0
4	Massangis yellow rock	13 h 8	59.2		48	105.2	2.409	10.32	93	2.23	5.22	0.0159
5	Euville rock	5 h 21	109.4		106.8	536.4	2.259	14.75	97	4.23	3.24	0.12
6	Lavoux fine	2 h 58	427.5		116.4	3.848	1.932	28.00	98	18.4	19.2	0.13
7	Saint-Maximin soft rock	1 h 56	828.6		116	11.154	1.708	36.33	82	35.9	40.2	0.35
8	Mery "banc royal"	57 m	1,384		139.8	21.521	1.609	40.12	78	27.8	32	0.40
9	Billy "banc royal"	55 m	1,490		416.6	7.136	1.588	42.58	86	32.3	38.9	0.85 to 1.5

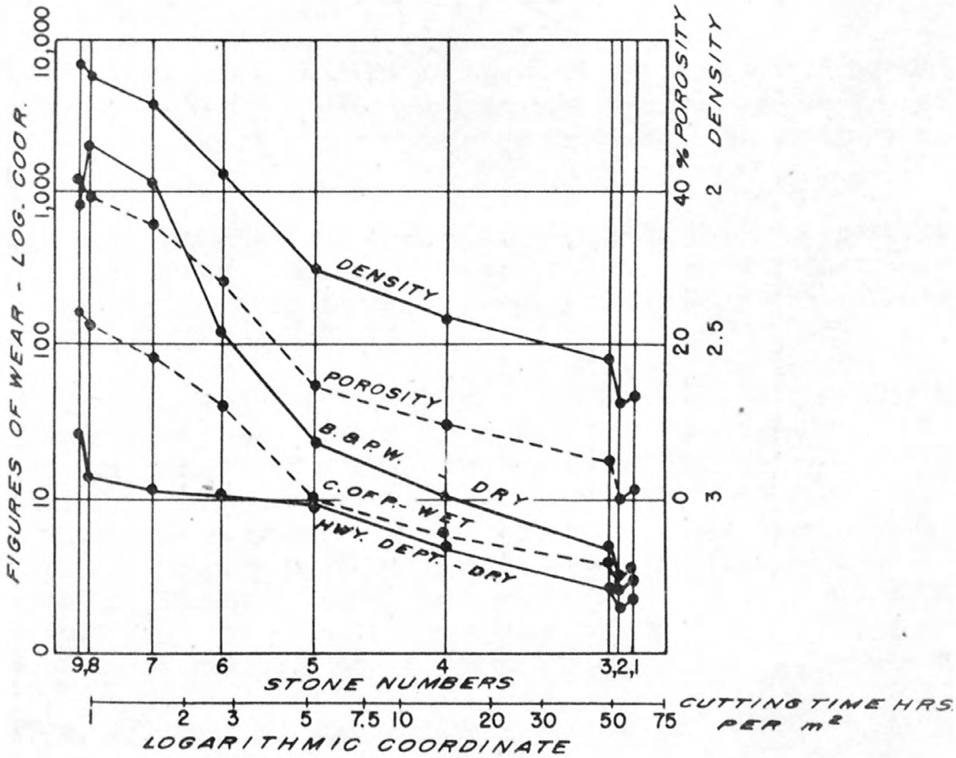


FIG. 3.- VARIATIONS OF WEAR, DENSITY, AND POROSITY IN RELATION TO CUTTING TIME

On figure 4, the logarithm of cutting time is represented on the abscissae, the density on the ordinates. It will also be seen that, except in the deviation of stones 1-2, the density allows the classification of the stones in the same order, the hardest stones being the most dense.

The same diagram also shows that the difficulty of cutting is related to the resistance in a rather linear manner when the resistance is given in logarithmic coordinates; so that:

$$\log. R = 0.77 \ \log. T + 1.78, \text{ where}$$

R = crushing strength on cubes of 8 cm tested in dry condition.

This formula can also be written:

$$T = \left(\frac{R}{60}\right)^{1.30} \qquad \text{or simplified} \quad T = \left(\frac{R}{60}\right)^{\frac{4}{3}}$$

Evidently such determination of the cutting time according to the resistance can only serve for a first approximation and has no precise value. This comparison between two stones can only be made when the cutting times are very different.

On figure 4, the chemical composition expressed by the percent of lime carbonate is also shown compared to cutting time. No distinctive variation is seen, the percentage varies in an apparently irregular manner from seventy-eight to ninety-eight percent.

Figure 5 shows the coefficient of wear according to density, the coefficient of wear being represented on logarithmic coordinates and the density on normal coordinates. The results of the tests made using the method of the City of Paris fall into a straight line except for the scattering of the limits of variation of each rock marked on either side of the line. This confirms the effectiveness of the method in wet condition which, by removing the wear dust immediately after its occurrence, prevents the clogging of the material and keeps it at all times in a state comparable to its original state; also the stone dust does not mix with and changes the qualities of the abrasive.

The VP coefficient of wear can be given according to density by:

$$\log. u = 5.70 - 1.6 D,$$

where D is the apparent density.

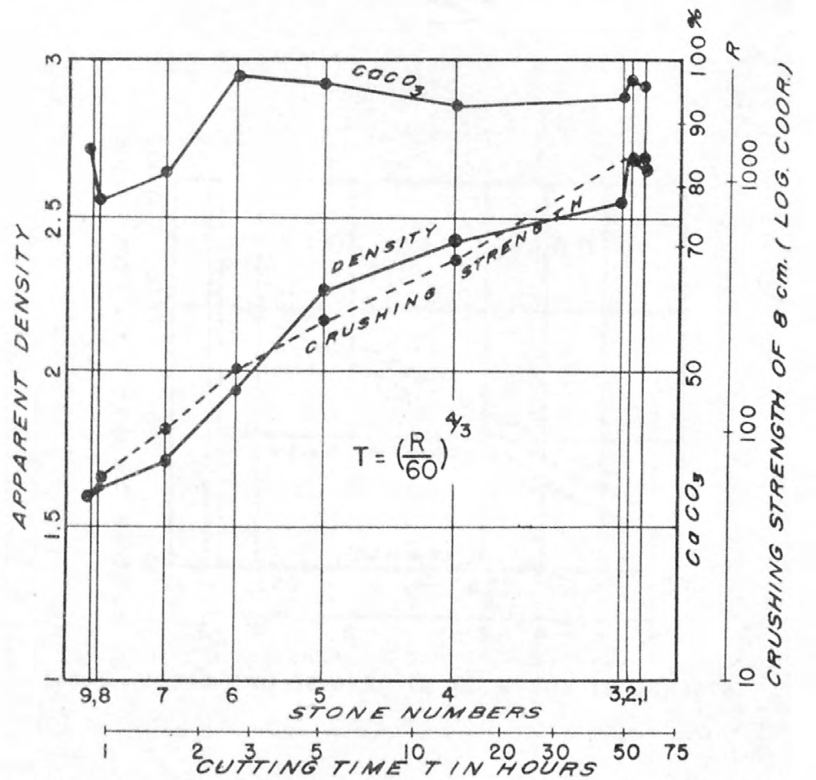


FIG. 4 - VARIATIONS OF $CaCO_3$, DENSITY AND CRUSHING STRENGTH IN RELATION TO THE LOGARITHM OF CUTTING TIME.

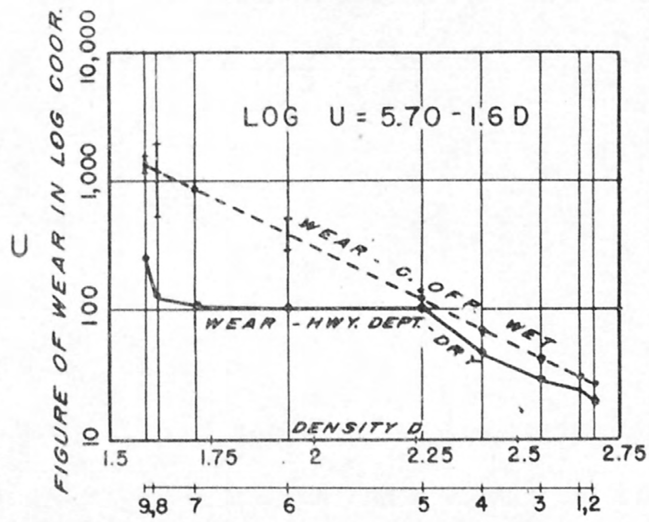


FIG. 5.- VARIATION OF WEAR IN RELATION TO DENSITY

The column before last in Table II gives the results of the capillarity test. The detail of this test which was devised at the request of Afnor has been described by Mr. Feret. It is seen that the result is given by the characteristic constant $C = \frac{100\rho}{s\,t}$, where ρ is the weight of water absorbed by capillarity during a period t for a test specimen of section s in cm^2. It was observed that for a very long period after starting the test the quantity of water absorbed was proportional to the square root of the time elapsed from the beginning of the test. As an example, let us consider a capillary tube of radius r, the bottom of which remains in water.

The relation between the height x reached after a period t by a liquid of viscosity η and density ρ is:

$$t = \frac{8\eta}{\rho r^2}\left[x + L \log\left(1 - \frac{x}{L}\right)\right]$$

where L is the limit of height reached after an infinite time. To simplify, for the small values of x, the logarithm in series can be developed, and

$$t = \frac{Ax^2}{r^2}\left[\frac{1}{2L} + \frac{x}{3L^2} + \ldots\right]$$

by keeping the first term only:

$$t = \frac{Ax^2}{2r^2L}$$

which gives:

$$x = r\sqrt{\frac{2L}{A}}\;\sqrt{t}$$

Consequently, the rising of the water at the beginning of the operation is proportional to the square root of the time. One is not able, however, to anticipate the maximum height of rising because, although we know $A = \frac{8\eta}{\rho}$, the average value of r is unknown.

The theoretical calculation cannot be carried further, for if the stone has intermingled capillarity canals of various diameters, the analogy with a group of tubes could lead to errors.

The coefficient of capillarity which represents the rising at the beginning of the test, gives the desired information as regards the practical use of the material.

On figure 6, the value of coefficient C is represented on normal ordinate as a function of porosity_/. It is seen that the points fall into a parabola

---

_/ The capillarity on bedding alone seemed to be of interest. Capillarity perpendicular to bedding is generally higher and in any case more irregular.

---

which gives the empiric formula $C = \frac{1}{44}p^2$ which is very satisfactory for practical needs.

On the same figure 6, the density as compared to porosity is represented on ordinates. The points fall into a straight line having an equation:

$$P = 0.95 \left[1 - \frac{D}{2.80}\right]$$

This relation shows that the absolute density of limestone is about 2.80, which was already known, while on the other hand, the porosity test permits filling of only ninety-five percent of the voids, five percent remaining impervious to water under the testing conditions.

The permeabilities obtained by the method developed by Mr. Feret are shown in the last column of table II. The numbers are expressed in grams per cm of thickness, per cm of the section, per kg. of pressure, and for a duration of one hour. They are indicated on figure 7 which shows that the permeability increases rapidly with the porosity, approximately with the cube of porosity.

Poiseuille's law implies that for a capillary tube the flow increases with the fourth power of the radius, therefore with the fourth power of porosity. This shows that the solid under consideration cannot simply be compared to a group of tubes.

In table III, other results of tests of similar materials have been summarized. These results refer mainly to strength.

Figure 8 shows, as compared to density, all the measures of resistance made on cubes of 7, 8, 30 and 50 cm. Generally the cubes of 50 cm give a lower resistance than the standard cubes of 8 cm, the fall in resistance being from twenty to thirty percent except for hard stones, where the presence of veins and sutures is strongly felt, and in which a fall in resistance is still more pronounced. Consequently it is noted that the resistance on cubes of 8 cm cannot be used for the calculation of construction work except if a coefficient of reduction from 0.70 to 0.50, according to hardness, is applied.

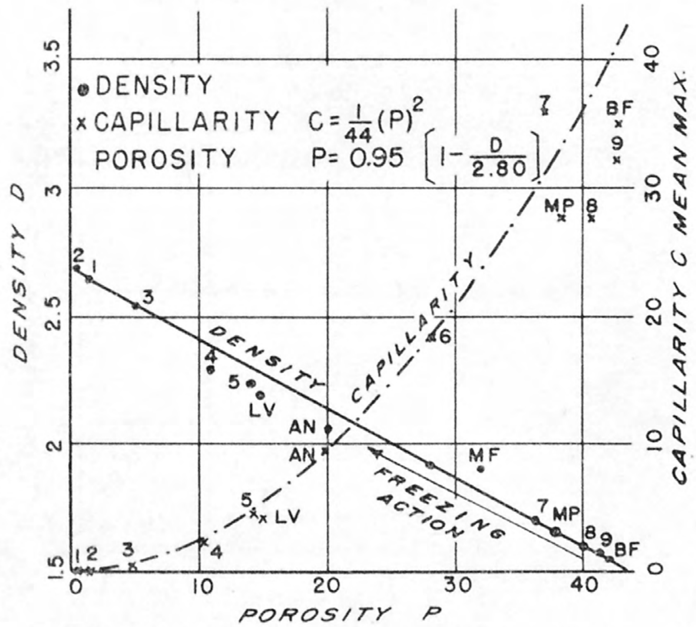
Figure 8 shows the results given by the Mesnager formula which estimates the resistance as compared to density:

$$R = 150 \left[\frac{D - 0.83}{2.82 - D}\right]$$

It is seen that this formula is about correct except for the soft stones (8 and 9) when the resistance on 7 cm cubes is under consideration. This formula gives the highest figures that we obtained; consequently, it is particularly optimistic. It could well be replaced by a logarithmic function which would give a straight line using this system of coordinates and in which it would be found that:

$$\log R = 1.24\, D - 0.25 \text{ for the 8 cm cubes}$$ /

/ Either of the two formulas can only give a more or less approximate value. It is noted, however, that in particular for hard stones the Mesnager formula gives the highest limit of resistance and the logarithmic formula gives the lowest limit.



Translator's note: The crosses marked MP, BF, LV and AN apparently refer to additional samples.

FIG. 6.- VARIATION OF CAPILLARITY AND DENSITY AS COMPARED TO POROSITY

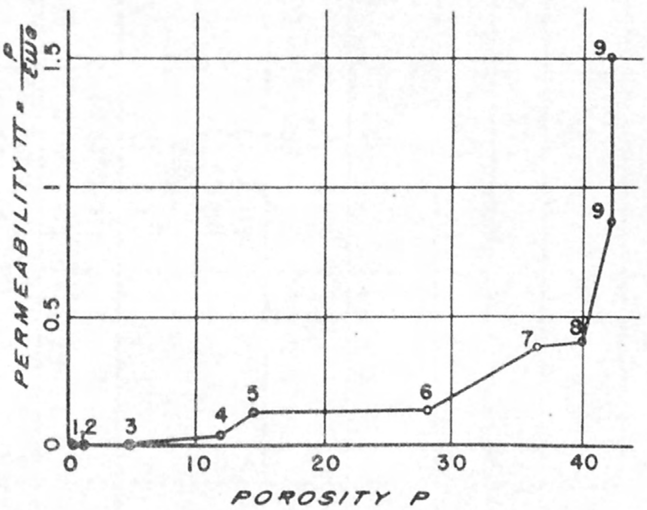


FIG. 7.- VARIATION OF PERMEABILITY AS COMPARED TO POROSITY

Table III 1/

No.	Name	Resistance to compression on 7 cm cube				Resistance on 8 cm cube AFNOR	Resistance on 50 cm cube parallel to bedding	Tensile strength		After freezing	
		Parallel to bedding		Perpendicular to bedding				Parall. to bedding	Perpend. to bedding	Condition	Resistance (8 cm)
		Dry	Wet	Dry	Wet						
1	Hauteville	1,447		1,370		1,265	2/ 610 (sutures)	108	118	intact	1,250
2	Comblanchien	1,367		1,347		1,296	2/ 665 (veins parallel to bed)	69	95	intact	1,300
3	Larrys spotted	1,095	1,070	1,221	1,196	1,234	2/ 890	101	123	intact	1,200
4	Massangis yellow rock	670	524	830	598	455	380	92	104	intact	355
5	Euville rock	397	307	278	283	277	280	22.3	33	intact	230
6	Lavoux fine	196	126	169	97	189	141	29.3	31	fissures	45
7	Saint-Maximin soft rock	143	94	81	64	106	70	11.8	27.2	fissures	49
8	Mery "banc royal"	72	38	55	32	62.5	47	13.8	17.5	disintegrated	13.5
9	Billy "banc royal"	61	35	56	30	51.8	37.6	11.5	14.6	disintegrated	14.5

1/ 30 cm cube for 1, 2, 3. - 50 cm cube for the others.
2/ Resistances are given in kg/cm^2.

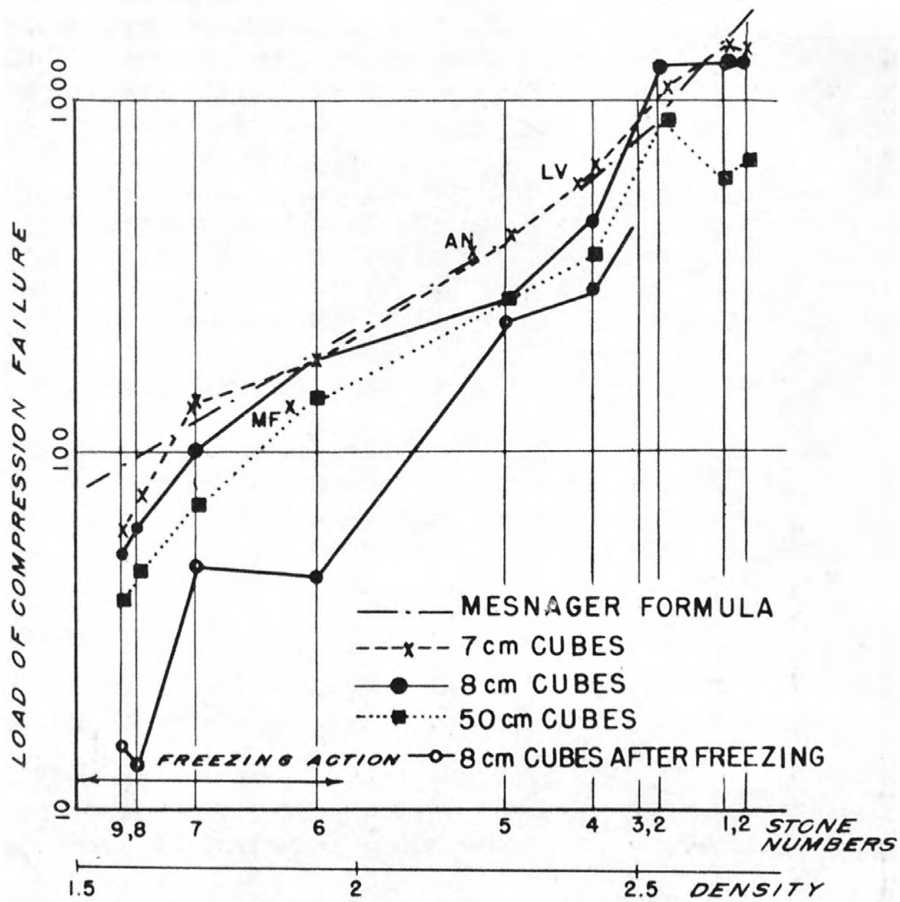


FIG. 8- VARIATION OF COMPRESSION STRENGTH OF THE DRY STONES COMPARED TO DENSITY FOR VARIOUS SIZES OF CUBES

Translator's note: The crosses marked MP, BF, LV and AN apparently refer to additional samples.

Figure 9 gives the strength of stones parallel to bedding, in dry and wet conditions, and perpendicular to bedding in dry condition. The softer the stone the smaller will be the strength perpendicular to bedding as compared to the strength parallel to bedding; the influence of the orientation of the crushing stress does not seem to matter for stones 1, 2, 3 and 4.

Also, the softer the stone, the greater the influence of moisture; the ratio $\frac{R \text{ perpendicular to bedding}}{R \text{ parallel to bedding}}$ varies between 0.82 for Billy (no. 9) and 1.0 for Comblanchien.

The freezing tests are summarized in the two last columns of table III. Stones 1 to 5 remain apparently intact after twenty-five freezing and thawing cycles, whereas stones 6 and 7 crack and numbers 9 and 10 disintegrate. The strength after freezing given on figure 8 shows that stones 6 to 9 are frost-riven as they show a great fall of compressive strength (more than fifty percent). The effect of freezing is consequently important for a density lower than two; it is still noticeable and acts on the resistance to compression without apparent disintegration of the stone if the density is lower than 2.5, consequently for stones 4 and 5 the fall of resistance is thus from ten to twenty percent and the effect of freezing is hardly perceptible for stones 1, 2 and 3. If the freezing test itself does not eliminate the stones, it must, however, be taken into account when computing the resistance to compression, and the establishment of rates of safety must be determined consequently.

After the study of compressive strength, measurements were made regarding the stone deformation. Plastic and elastic strains in dry and wet conditions obtained are given in table IV, also the coefficients of total strain (elastic plus plastic) in wet condition (maximum strain coefficient of the stone ω).

If coefficient E is known, the elastic strain Δ under a load F per cm^2 can be indicated by the formula $\Delta = \frac{F}{E}$. The results of strain measurements are given by figures 10 to 16.

The coefficient of total strain was determined from the uniform load of 30 kg per cm^2; it remains fairly constant for higher loads except near the rupture point where it increases considerably.

Figure 17 gives the coefficients of elasticity compared to density. It seems to show a systematic increase but with much irregularity.

Table III also gives the tensile strength obtained by calculation after flexure tests on prisms of 7 by 7 by 28 cm. The Navier formula was applied in which the average reaction is assumed to be halfway up. Here, in contrast to what happens in the crushing tests, the strength parallel to bedding is lower than the strength perpendicular to bedding, which is as it should be. The variation of these resistances with the density is given by figure 18. It is seen that stones are divided into two distinct categories: stones that resist well to traction (from 70 to 125 kg/cm^2): nos. 1 to 4; and stones which do not resist well to traction (from 10 to 30 kg/cm^2): nos. 5 to 9. Here also there is no perceptible relation to the other properties.

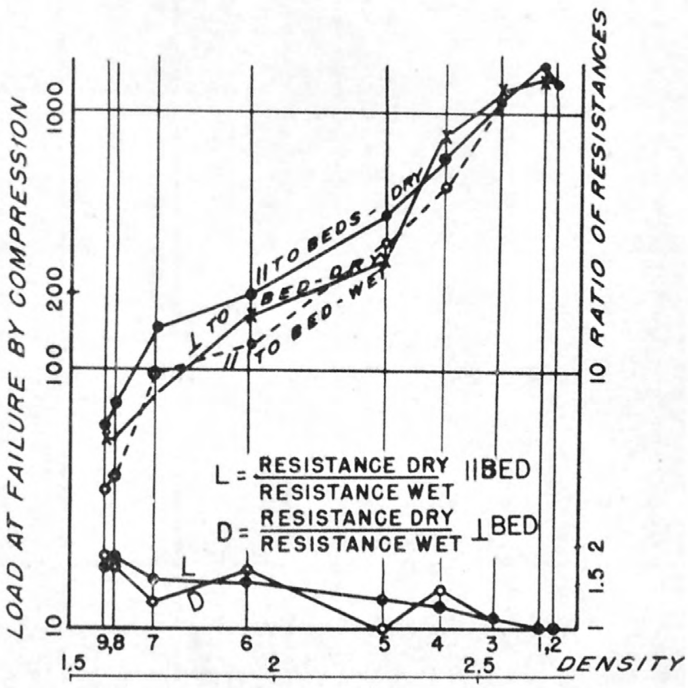


FIG.9 - RESISTANCE OF DRY AND WET STONES PARALLEL TO BEDDING AND PERPENDICULAR TO BEDDING

Table IV

No.	Name	Coefficient of elasticity in kg/cm^2		Coefficient of total deformation	Swelling due to water x 10^6	Thermal Expansion x 10^6
		Dry	Wet			
1	Hauteville	640,000 to 700,000	640,000 to 700,000	640,000 to 700,000		1.4
2	Comblanchien	685,000 to 700,000	685,000 to 700,000	685,000 to 700,000		1.5
3	Larrys, spotted	540,000 to 670,000	540,000 to 670,000	540,000 to 670,000	134	1.5
4	Massangis, yellow rock	605,000	450,000	400,000	234	6.4
5	Euville rock	220,000 to 440,000	220,000 to 440,000	200,000	17 to 40.7	13.3
6	Lavoux fine	400,000	260,000	260,000	90	3.1
7	Saint-Maximin, soft rock	70,000	116,000	62,500	129	6.6
8	Mery, "banc royal"		57,000	43,000	225	3.3
9	Billy, "banc royal"	61,000	36,000	30,000	160	6.8

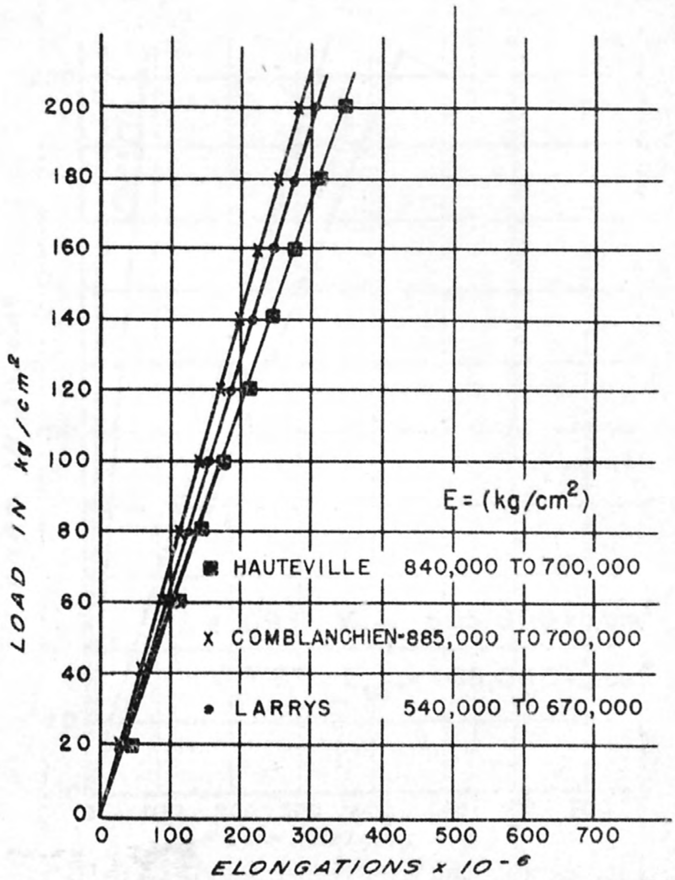


FIG. 10 - DEFORMATIONS OF LARRYS SPOTTED, OF COMBLANCHIEN AND OF HAUTEVILLE

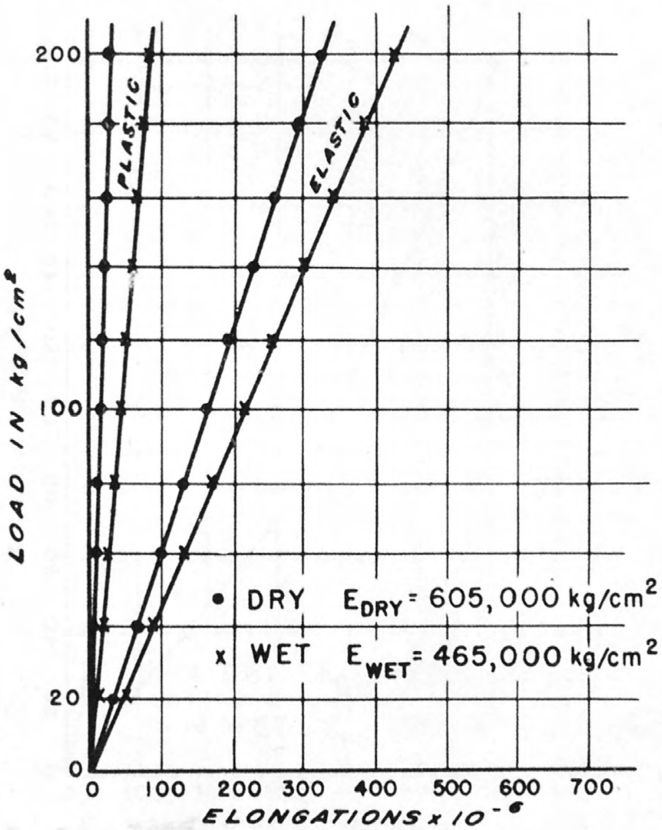


FIG. 11 - DEFORMATION OF MASSANGIS YELLOW ROCK

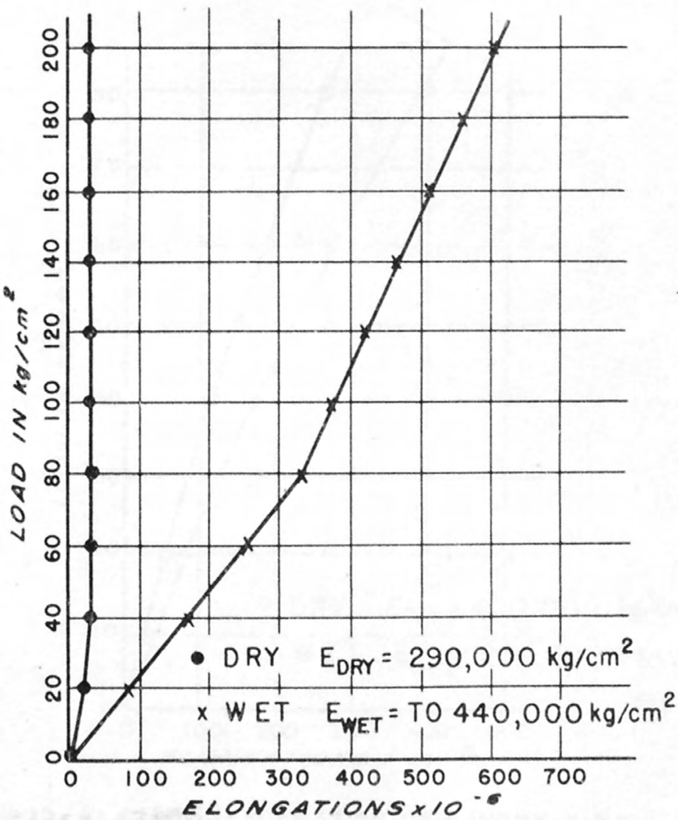


FIG. 12- DEFORMATION OF EUVILLE ROCK

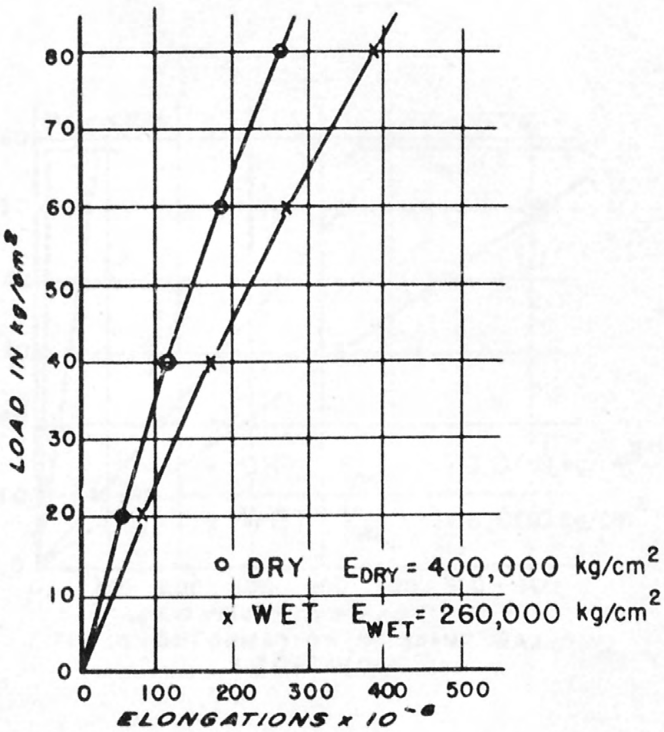


FIG. 13 - ELASTIC DEFORMATION OF LAVOUX, FINE

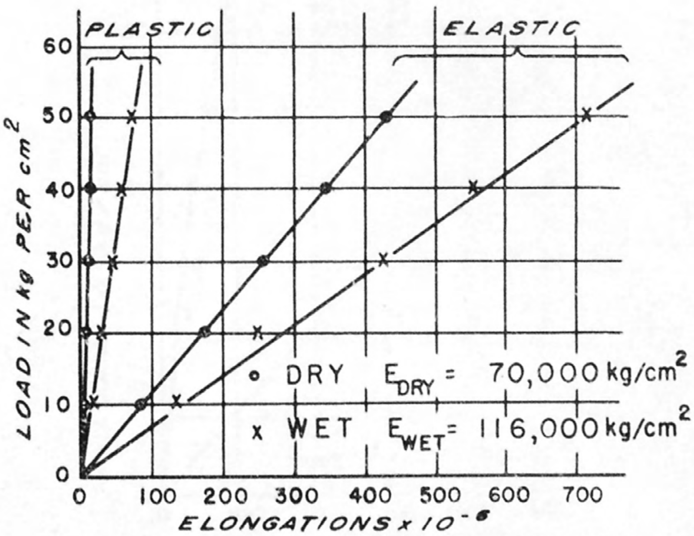


FIG. 14 - DEFORMATION OF SAINT-MAXIMIN, SOFT ROCK

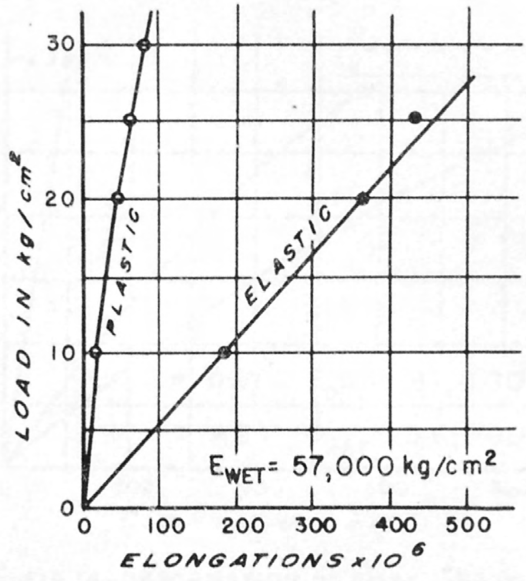


FIG. 15 - DEFORMATION OF MERY, "BANC ROYAL" WET.

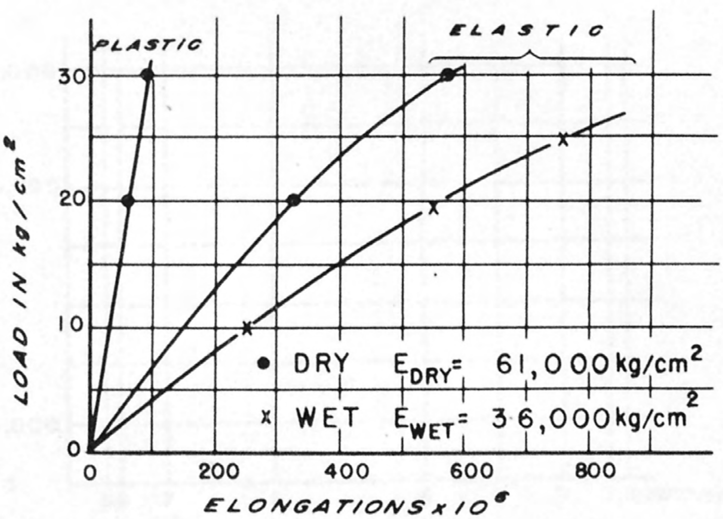


FIG. 16 - DEFORMATION OF BILLY, "BANC ROYAL."

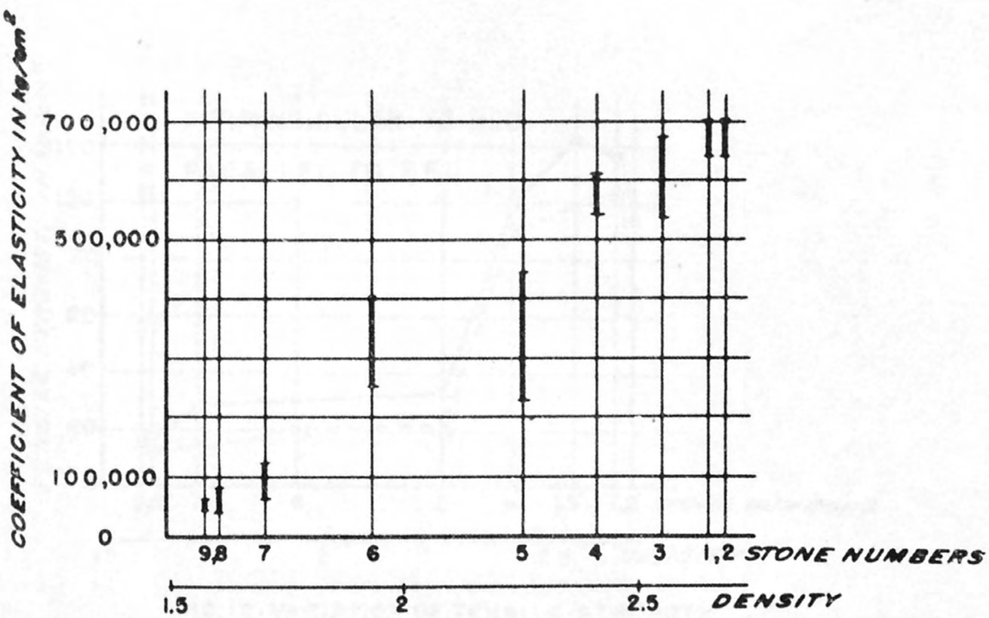


FIG. 17 - VARIATION OF THE COEFFICIENT OF ELASTICITY COMPARED TO DENSITY

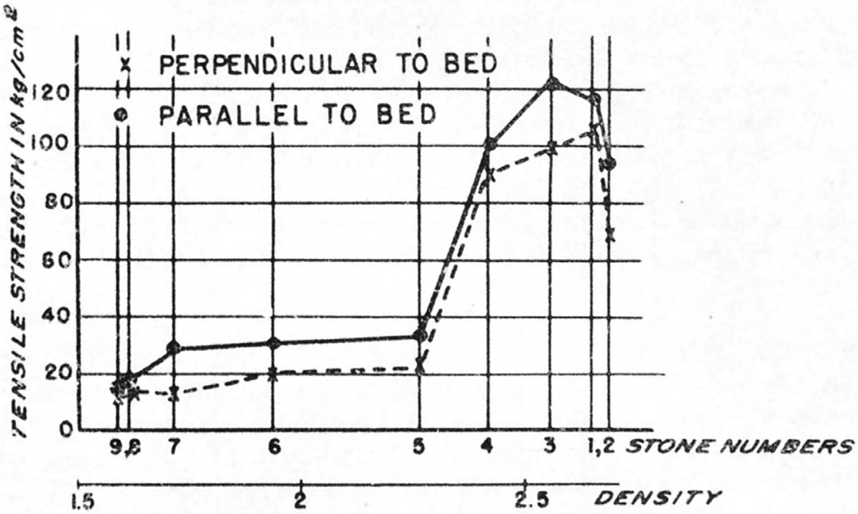


FIG. 18-VARIATION OF TENSILE STRENGTH COMPARED TO DENSITY

Stones in damp condition will swell; this well-known phenomenon is similar to what happens in cements. It is a capillary phenomenon due to the introduction of water films which by their superficial pressure separate the solid grains. The swelling is consequently dependent on the structure and the figures given in table IV show its irregularity. Its variation does not seem to depend upon the other properties. The increase of the length of the stone may be as great for some hard stones (Massangis, Larrys) as for soft stones. The maximum reached is 234×10^{-6} _/.

_/ It will be noted, however, that the greatest swellings are related to the highest alumina contents (massangis, Mery and Billy). It is probably due to the presence of clay, which as it is known, increases its volume in the presence of water.

The last column of table IV gives the coefficient of thermal expansion. The results on figure 19 show some inconsistency in the figures which vary from 1.4 to 13.3 ($\times 10^{-6}$).

The test regarding the condition of the surface of the stone comes at the end of the series of tests. The purpose of dressing a stone is to reach a definite condition of surface which may be called rough-sawed, bush-hammered, ground, polished, etc. These are technical terms, for which it would be desirable to apply actual figures. To this end, I asked Mr. Canac, Director of the Center of Scientific Researches of Marseille, to see if it is possible to define the surface condition by an optical method. The studies are not yet completed and will be the object of a special note. However, it is possible now to give some indications of the process followed and of the first results obtained.

The face studied being AB (fig. 20) a light ray (LO) is directed on this face forming an incident angle α with a line normal to the face; the ray is reflected at O, then it is diffused in different directions according to the relief of the surface. To measure the diffusion, a photo-electric cell is placed at C. It is made to move along the quadrant of circle C_1C_2 located in the same plane as OL, so that the intensity of each one of the reflected rays of this plane is measured. A reflection spectrum characteristic of the condition of the surface is obtained in this manner. As an example, figure 21 gives the different spectra for a value of α equal to 20° obtained on the Hauteville stone. The sawed face (1) shows a few oscillations, the bush-hammered face (4) brings about a uniform diffusion and gives little reflection. Face (3), perfectly polished, shows a point under the twenty degree angle symmetric to the incident angle; it gives a very clear specular effect. In face (2), worked for the test of difficulty of cutting, the specular effect is small but it exists, as shown by the rise at around twenty degrees.

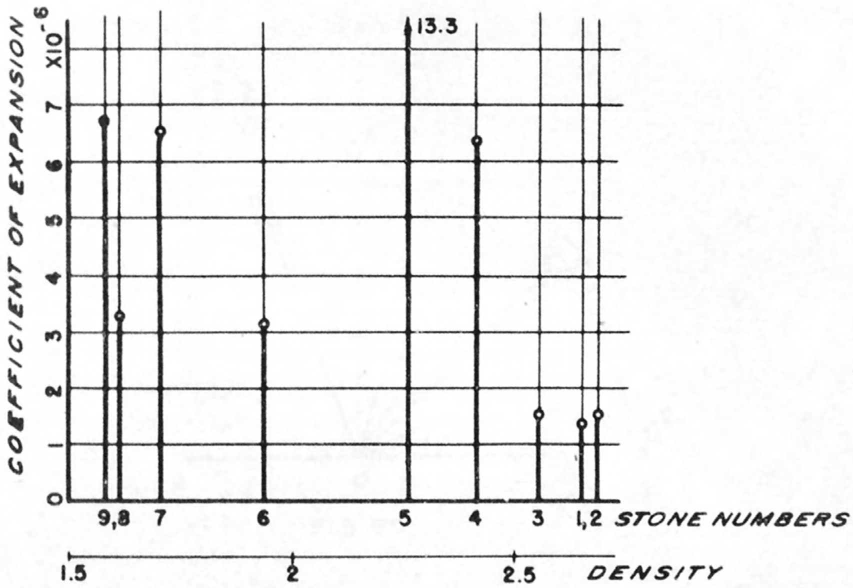


FIG. 19 - COEFFICIENTS OF THERMAL EXPANSION

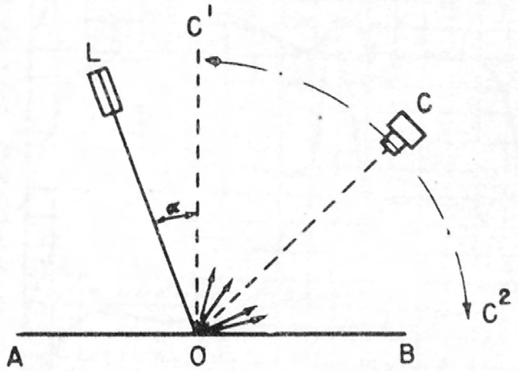


FIG. 20

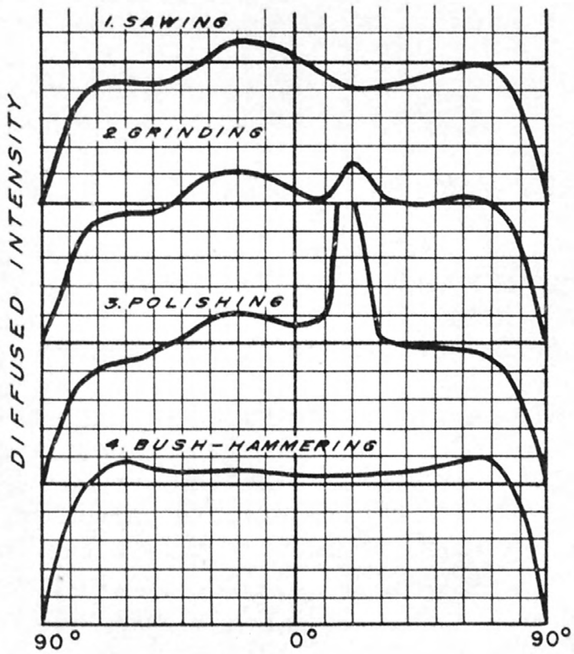


FIG.21.- HAUTEVILLE STONE

Maximum intensity of radiance reflected at twenty degrees for three stones:

Hauteville:	Bush-hammered	32
	Sawed	28 to 33
	Worked	45
	Polished	58
Comblanchien:	Bush-hammered	32
	Sawed	31 to 35
	Worked	44
	Polished	56
Larrys, spotted:	Bush-hammered	32
	Sawed	35
	Worked	32
	Polished	54

The relation of the radiance from a polished surface to the radiance from a bush-hammered surface is in every case included between 1.7 and 1.8.

It will be seen later whether or not these figures have a technical character and are able to serve for practical purpose.

To sum up, the following points are to be especially stressed:

1. The time of cutting, determined by the time spent, can be related to resistance to wear following the VP method in wet condition.
2. The time of cutting classifies the stones in the same order as density, porosity, permeability, and crushing strength (save for a few unimportant exceptions).
3. Capillarity and porosity are directly related to density.
4. Crushing strength varies according to the condition of moisture of the samples, but in general it is related to density.
5. Tensile strength, elasticity, plasticity, chemical composition, thermal expansion, and swelling by water, have variations impossible to relate to other properties. Only a few general tendencies can be shown outside of any precise law.

It is to be hoped that the work will not stop here and that later on other types of stones will be studied in order to increase our knowledge and to define the general laws which we are now only coming in sight of. This depends as much on the quarriers as on us. Encouragement for the continuation of our work will show if we performed useful work, which is our greatest desire.

Supplementary Note

(September 1943)

It has been mentioned that the irregularities observed between the Comblanchien and the Hauteville stones may have come from a defective supply of this last stone. New samples were sent later on to the laboratory and gave the following results:

Hauteville (second series of tests)

Density	Porosity	Crushing Parall. to bed. 8 cm cubes	Crushing Perpend. to bed. 8 cm cubes
2.673	0	1,421	1,421
2.692	0.1%	1,765	1,234
2.672	0.1%	1,500	1,640
2.697	0.1%	1,593	1,015
2.701	0	1,609	2,156
Averages:			
2.697	0.06%	1,577	1,493

The following facts are noted (see tables II and III):

a. The average porosity is really smaller than for the Comblanchien.
b. The apparent density is really higher than for the Comblanchien.
c. The crushing strength is definitely higher than for the Comblanchien, although there is a great range of results.

These new characteristics, if admitted, may do away with the anomaly which caused the deviation at the end of the property curves. This confirms the theoretical conclusions of our study, namely that the crushing and the wearing strengths are increasing functions of density, while porosity is a decreasing function of density. The empiric formulae which we indicated, give more or less crude approximations which allow us to estimate a range of values. A disconcerting fact remains, however, disclosed by this incident: a stone sent with a specified qualification is subject to variations of properties greater than the differences between two types of stones of closely related nature. This is a cause for reflection by the users.

Discussion

Mr. Duvernin. - Has the question of quarry water been studied? And in what form?

Mr. L'Hermite. - No, I did not study the question.

Mr. Duvernin. - Quarry water is loaded with calcium carbonate which crystallizes on the surface of the stone during its evaporation. If a stone is cut when containing its capillarity water, it shows a hard surface, but if it is cut when the water is gone the surface is not as hard. I think that is the reason which explains the differences of results between large and small samples. The specifications of the Highway Department require for the blocks of stone to remain, as much as possible, a whole winter in the quarry before being used.

On the other hand, regarding the reflection power experienced by Mr. Canac, I want to mention that a similar work is done by Mr. Orcel for the determination of minerals on polished surfaces.

Mr. L'Hermite. - The question of capillarity water is not well known and one should beware of any interpretation before studying it closely. I do not believe that this influence caused the strength to vary according to the size of the specimen as all the cubes of different dimensions were taken from the same block after this block remained more than six months in the atmosphere of the laboratory. I will also mention that it is asserted that the freezing of stones varies according to whether they have just come out of the quarry or have been dried, but I have no experimental proof of this.

Mr. Prot. - How do you explain the difference of crushing strength? According to the size of the different cubes which are really similar test-specimens?

Mr. L'Hermite. - Numerous parameters occur; the influence of defects, faults, sutures, increases when the stone is larger. On the large cube of comblanchien which we tested, the rupture started along a vein and led to the breaking down of the rest. Besides there is the influence of surface friction which becomes less important as the surface of the cube in contact with the plate of the press gets larger. As a matter of fact, rupture by double pyramid is always observed on small cubes, while on large cubes vertical fissures without double pyramid can be seen. The transverse swelling of the stone when compressed causes tangential stresses on the bearing faces which produce an effect of binding on the material near the faces. When the cube is large, the tangential stresses first become very important, they exceed the resistance to sliding of the stone on the plates of the press and the surface becomes suddenly liberated. The tangential stresses then decrease, as well as the resulting binding effect. The binding effect becomes relatively much weaker than in the case of small cubes and the crushing strength decreases in the same proportion. On high cylindrical test-specimens, the stone rupture occurs through sliding along some definite planes and then follows the expectations of the theory.

These sliding planes are more inclined, measured from the bearing faces, as the stone is more resistant. The ideal for our tests would have been to use double-headed samples similar to what I used for the study of concrete and which I have already described several times. Unfortunately, it is difficult to cut such test-pieces; it would be very expensive and complicated.

Mr. Dobes. - I must make a purely formal remark concerning one of your graphic tables. You have shown the strength parallel and perpendicular to bedding with abscissae proportional to density and logarithmic ordinates. The logarithmic ordinates are used in many cases, but here very little difference is seen between the ordinates of the diagrams. I consequently believe that it would be desirable to show the results on natural scale.

Mr. L'Hermite. - It is not easy, if not impossible, because the strength varies from 15 to 1,200 kg. Moreover, I believe that one can very well read the reports on the diagrams at the bottom of the figure and, in any case, for more precision, one can refer to the tables.

A member of the audience. - Is not the divergence between the crushing strength in dry and wet conditions related to Mr. Freyssinet's ideas?

Mr. L'Hermite. - It is possible that this phenomenon can be interpreted by taking capillarity into account. The same applies, moreover, to swelling under the influence of water.

Mr. Loup. - The influence of capillarity water must have a similar cause.

Mr. L'Hermite. - Maybe.

A member of the audience. - It happened that stone which remained in water for numerous years has become extremely soft.

Mr. L'Hermite. - There may be then solution of some salts.

Mr. Mesnager. - Do the results you just gave apply to other stones?

Mr. L'Hermite. - They probably apply to most limestones. I have given on the diagrams some results obtained from calcareous stones and which seem to follow perfectly the general laws which we have just defined. On the other hand, I have no idea of what may happen for materials chemically different such as granites, basalts, etc.

Mr. Duvernin. - I believe that even among the limestones there must be materials giving aberrant results.

Mr. L'Hermite. - It is possible that some divergences appear when it is a question of a very particular crystalline structure. That is why I do not believe that the question is definitely settled and I think it is useful to pursue our researches on the maximum of materials from different origins.

Tests and researches on calcareous stones

Note from the Union of Quarrymen of France

The Union of Quarrymen read with great concern the very interesting report of the works made on building stones by Mr. R. L'Hermite, Director of the Laboratoires du Batiment et des Travaux Publics (Laboratories of Building and Public Works) and by Mr. L. Feret, Chief of the Laboratory.

The union believes it will be conformable to the general interest to express two remarks on this subject; one of these remarks will bring light on the discussion regarding the variations noted on stones of similar nature, and the other remark will remove the confusion which these variations seem to have brought in the mind of the users.

The variations noted recall opportunely that, according to the place a sample of stone occupied in the formation, it may present characteristics other than those of another sample taken from a different ledge in the same quarry.

That is a fact well known to the quarry owners, and it is nothing for them to be able to distinguish the quality of the rock and to choose, according to its utilization, the pieces which show the greatest strengths and the best constructive properties.

Had the Quarrier Association been informed that the samples requested for the manual cutting were to serve for tests, the results of which would establish the comparison of the stones among themselves, that is a scale grading from the hardest to the softest stones, and that these samples were to constitute a series of standards which in the future, by referring to these results, would permit the classification of the nature of building stones, the Association would certainly have indicated a common method for the determination and the taking of samples, so that the results of the tests could be usefully compared among themselves.

This common method has since then been perfected and before long will be standardized.

For lack of taking this precautionary measure, anomalies were bound to be revealed in the results.

The authors of the study, in view of the variations noted in the two series of tests made on a stone of the same origin concluded hastily that: "there is a cause for reflection by the users."

No doubt, they must consider it, but first of all, they must consider the fact that when natural products, such as stones, are concerned, it is advisable to establish not only the requested origin, but also the quality. For instance: Massangis rock, Massangis hard limestone, Saint-Maximin soft rock, etc. Thus, one will avoid facing variations which at first seem surprising.

Besides, they must know that in this respect, nothing can thoroughly replace the references to material which withstood the ravages of time.

The studies undertaken present a real interest, but the results should not exempt producers and users from knowing their trade.

As a conclusion, the Association of Quarrymen of France considers that the said studies should be pursued, but that all necessary precautions should be taken so that the conditions of sampling and testing might be compared among themselves. The union believes that before publishing the results, it is advisable to interpret them in agreement with the tradesmen. The Association of Quarrymen of France remains at the disposal of the laboratory technicians to bring their contribution toward the perfection of this study.