EXPERIMENTS

UPON THE

Transverse Strength and Elasticity of Building Stones.

By THOS. H. JOHNSON, C. E. M. A.

When the Board of State House Commissioners for the State of Indiana assumed the duties of their office, one of their earliest acts was to investigate the relative merits of the different building stones that might be available for the new State House. In the course of these investigations they procured samples of many building stones, both from quarries in the State of Indiana and in other States. These samples were of two forms, cubes two inches each way and bars one inch square and fifteen inches long. Specimens of the two-inch cubes from each quarry were sent to Maj. Gen. Q. A. Gilmore to be tested for resistance to crushing, and his report upon the same was published by the Board of State House Commissioners in their "*Report No.* 6," January, 1879. The one-inch square bars were placed in the "Stone Room," in which the Board of Commissioners have accumulated a fine cabinet of samples of various building materials. Through the kindness of the Board the writer was furnished with samples of these one-inch bars, so far as there were duplicates in their collection.

At the time these tests were made the samples were about one year old, and were therefore thoroughly seasoned. They were tested under transverse strain and the deflection under each application of the load carefully measured. From each deflection so measured, and the load producing it, the Modulus of Elasticity was calculated, and the Modulus of Rupture from the load under which the specimen broke.

The term "Modulus of Elasticity" is used by writers on strength of material to designate the *unit* or standard of measure of the elasticity of a material, and is an arbitrary and hypothetical quantity. All materials, however solid and rigid apparently, will stretch under tension, and shorten under compression, to an extent which may be measured if appliances of sufficient delicacy be used. Having found the rate at which any material will stretch under a given pull, we may calculate the force that would be necessary to stretch it to double its original length, supposing that rate of stretch could continue without breaking the material. The amount of that force, in pounds, would be the "Modulus of Elasticity." The same force that would stretch it to double its length would, if applied as a push or compression, shorten the piece to one half its length. Under transverse strains, the amount of bending depends on the amount of stretch along the bottom, and shortening along the top of the bar; and hence the measured deflections enable us to determine the modulus of elasticity of the material.

The modulus of rupture is the load that would break a beam one inch square, resting on supports one inch apart, the load being applied at the center.

The machine on which these tests were made was constructed from designs by the writer, and consists of an upright rectangular frame, with a double cross-bar a little above the center, on which are two knife-edge bearings on which to rest the test piece. These bearings are movable along the cross-bar so as to be readily adjustable to the length of the test piece. At the center of the test piece is a saddle carrying a stirrup on a knife edge, bearing over the center of the saddle. A dynamometer connects this stirrup to an eye in the top of a screw, which passes through a hand-wheel-nut attached to the lower cross-bar or sill of the frame. The dynamometer has a capacity of four hundred and fifty pounds, and is graduated to intervals of five pounds. By using a second pair of attachment rings for lighter strains, the dynamometer will read to single pounds up to fifty pounds. The accuracy of the readings of the dynamometer was verified before using by putting it in a Rehle testing machine and subjecting it to measured strains throughout the whole range of its scale. By this arrangement of saddle, dynamometer and screw, each test piece could be readily subjected to transverse strains of measured intensity.

To observe the deflections the following device was resorted to: A cord made of silk fibres, laid parallel and wrapped with fine metallic wire, was attached to the saddle and carried up through a hole in the cap of the frame, where it passed around a small pully on a horizontal spindle, upon one end of which was a small plate glass mirror. From this spindle the cord passed along the top of the frame, to a pully at the side, from which the end of the cord hung free, and carried a counterweight which was adjusted to balance the weight of the saddle, dynamometer and their attachments, thus relieving the test piece of all strains excepting those applied by the screw and registered on the scale. The counterweight also served to hold the cord taut, and insure a proper motion of the mirror, following the deflection of the test piece. The amount of the deflection is measured by reading, through the telescope of an ordinary transit or level, a graduated scale as seen in the mirror. This scale is set up at a distance of ten feet from the mirror, and admits of reading the deflections accurately to $\frac{1}{10000}$ of an inch.

In making the tests the piece to be tested was first accurately calipered for dimensions and placed on the bearings. The wheel was then turned until the index of the dynamometer began to move, showing that the slack was taken up and that the test piece began to feel the strain. The whole was then slowly backed off until the index just touched zero. In this position the mirror was then adjusted to show the zero of the deflection scale on the cross-wire of the telescope. Strains were then applied, beginning generally with ten pounds, and increasing by ten pounds intervals until rupture occurred, the deflection at each increase of strain being observed by an assistant at the telescope.

The results are appended both in tabular form and in diagram.

As the pieces differed in their sectional dimensions, it was necessary for more ready comparison, especially in the diagram, to correct the recorded deflections, so as to get the deflections due to standard dimensions of one inch square. This was done in accordance with the established principle that the deflection is inversely proportional to the *breadth* and to the *cube of the depth*. These corrected deflections only were used in constructing the diagram, and are given in the table in the several columns headed "*corr.*"

The modulus of rupture was calculated from the formula

$$R = \frac{3\,P.\,l.}{2\,b.\,d.^2}$$

in which R is the modulus of rupture, P the load producing rupture, l length, b the breadth and d the depth of the test piece, all in inches. In this equation the weight of the test piece is neglected; but the error arising from this is very small, and does not materially affect the results.

The modulus of elasticity was calculated from the equation

$$E = \frac{P.\,l^3}{4\,\triangle.\,b.\,d^3}$$

in which E is the modulus of elasticity, $\triangle$ the deflection caused by a load P, and the remaining factors the same as before.

The diagram sheet shows three groups of lines having their origins of co-ordinates respectively at A, B and C. The group A embraces all experiments on oolitic limestone, in which the quarry beds were horizontal, and the mode of preparing the sample known. Group B embraces all other tests except sandstones, in which the loads were so small and the deflections so great as to require a different scale of platting in order to keep them within the limits of the paper. They are shown in group C.

Group B contains four experiments on oolitic limestones, Nos. 3, 18, 19 and 33. Nos. 3 and 33 were sawed vertically from the quarry ledge, making the beds at right angles to the axis of the bar, like a strip sawed off the end of a board. With Nos. 18 and 19 the mode of working was unknown.

RESULTS.

A very interesting result of this series of experiments is the apparent relation indicated between the *resonance* of the samples, and their *strength* and *elasticity*. I use the word "indicated" because it is imposible to get an exact measure of the resonance, or to describe it except by the use of such relative adjectives as "dull," "clear," etc., which have no exact meanings, and are incapable of mathematical comparison.

Each bar before testing was held vertically, lightly clasped between the thumb and finger, near one end, and then struck with some hard object, usually another piece of the same stone. Some of them (notably No. 1) would give out a clear, ringing, musical note. Others, such as the sandstones, would respond with a dull thud, like dried clay or putty. Between these extremes there were various degrees of resonance which could only be described in the crude way mentioned.

Prof. John Collett, now State Geologist, while a member of the Board of State House Commissioners, had repeatedly pointed out the difference in the resonance of the different samples, and had urged its importance as an indication of their relative strength.

Sound waves occurring singly or at irregular intervals impress the senses as *noise*, while regularly recurring waves are recognized by the ear as *music*.

In order that a body shall possess the property of resonance two conditions are necessary. The particles composing the material must be so intimately united as to transmit from particle to particle the force of the blow; and there must be sufficient elastic recoil and re-recoil to produce sustained vibration. The same physical properties, therefore, which give a material strength and elasticity, should also give it resonance in a nearly proportional degree.

In the absence of a measure of the resonance, I may say that throughout this series of experiments, as nearly as the ear could estimate it, the resonance of each piece tested was proportional to the modulus of elasticity as found from the test.

Passing from this to the more exact results, we find the most striking feature to be the very marked difference between the sawed and tool-dressed specimens of oolitic limestone. Indeed when attention is called to the subject, it becomes apparent that such difference must occur.

It is well known that a stone, however large, may be broken by striking a sufficient number of blows with a hammer, along the line where it is desired to break the stone. In this process the force of the blows is expended in gradually weakening the cohesion of the particles in a line following the direction of the blows. This weakening is increased by each successive blow, until finally rupture occurs.

If large stones may be thus broken, it is evident that the many blows, needed to dress a small sample by hand, must largely affect its internal condition. The blows, too, are uniformly distributed over all faces of the sample, so that all parts of the interior are equally affected. The small dimensions of test pieces (usually 2-inch cubes, for comparison, and in this series 1 inch bars), renders it certain that the disintegrating effect of the tool penetrates throughout the mass. It should not, therefore, be matter of surprise that the tool-dressed samples show lower results than the sawed samples.

It may be objected that the samples sawed and tool-dressed are from different quarries, and that the differences may be due to inherent differences in the stone, and not to the difference in the mode of working. But a glance at the diagrams will show that the two classes separate themselves into groups too distinctly marked to admit of such an explanation. If the difference between the groups fell within the range of difference between individual specimens in each group, this objection might have force. But such is not the case; the highest of the tool-worked does not reach the lowest of the sawed samples.

In order to show that the tool-dressing has in like manner affected the 2-inch cubes sent to Gen. Gilmore, the crushing strength as reported by him is given in the last column of the table.

It should be here stated that the cubes and bars sent from each quarry, were in each case, prepared alike, so that where my samples were sawed Gilmore's were sawed, and where mine were tool-dressed his were also tool-dressed, and his reported results have been classified on this assumption.

The average results of the two groups are presented in the following table, for more convenient comparison:

Average Results from Experiments on Sawed and Tool-Dressed Samples of Oolitic Limestone.

	MODULUS OF		
	RUPTURE.	COMPRESSION.	ELASTICITY.
Sawed	2,338	12,675	4,889,480
Tool-dressed	1,477	7,857	2,679,475
Ratio of tool-dressed to sawed	63%	62%	55%

The close agreement between these ratios is remarkable. Referring to the general table it will be seen that the average results for sawed samples is obtained from only four tests, and that one of these, No. 1, shows an exceptionally high elasticity. It is probable that if the number of samples had been greater, this exceptional case would have had less effect on the average modulus of elasticity, which would then have been less than here given. If we assume the average of the other three samples as more nearly representing the general average elasticity of that class of stone, then the ratio of the modulus of elasticity of the tool-dressed to the sawed samples would be 62¾ per cent. It would thus appear that the disintegrating effect of the tool is equally fatal to correct results in experiments on all modes of resistance.

These experiments show that owners of quarries who desire their stone to be properly set before the public should never allow tool-dressed samples to be submitted for testing purposes, and that the results of tests heretofore published have no value for purposes of comparison, where the mode of preparing the samples is unknown.

Referring again to the diagrams it will be noticed that the lines representing the sandstones and the tool-dressed granites approximate to the form of the parabola, while the sawed Oolitic limestones, together with the Niagara and Devonian group, are approximately straight lines. The tool-dressed Oolitic limestones show, in some instances, a tendency toward a straight line, and in others a tendency toward the parabolic form.

The straight line means that the elasticity is constant and unimpaired up to the instant of rupture. The parabola means that the elasticity is diminishing with each successive application of the load. In both cases the results are unique. With all other materials that have been made the subject of experiments, it is found that the line representing the test is approximately straight for the first portion of its length, and parabolic for the last portion, the change from the straight line to the parabola being usually well defined, and marked by a sharp cusp or point on the line. This point is called the "*limit of elasticity*," and it marks the load under which the elasticity of the specimen first becomes impaired. With the sawed limestones it would seem that the limit of elasticity is greater than the tenacity, and that the stone fails by tension along its lower surface before its elasticity has been impaired. With all those cases which show the parabolic form, the elasticity had been impaired by the tool-dressing, so that the limit had been passed before they were subjected to strain. The sandstones, however, were sawed, and the parabolic form developed by them was not the effect of tools, but shows a low degree of elasticity as inherent in the stone itself, and which renders them not well adapted for beams or lintels.

The Oolitic limestone, which forms the leading feature of the foregoing series of experiments, is so little known beyond the immediate neighborhood where it is quarried, that it may not be out of place to give here a fuller description of it and of its character as a building stone.

Geologically it belongs to the St. Louis group of the subcarboniferous period and has been formed from the crushed remains of the marine shells, corals, etc. These have been pulverized to the condition of fine sand; their soluble impurities washed away, and their insoluble residue reunited into solid rock by a deposit of carbonate of lime as a cementing material. Its structure is, therefore, that of a close grained, compact sandstone, while chemically it is a limestone of rare purity.

Like the sandstones, it works freely under the tool, while the homogeneity of its particles and binding material enables it to be worked to a clean, sharp arris. Like the sandstones, also, and unlike other limestones, its formation in the ledge is massive and solid; not stratified with clay partings. It has no well defined cleavage in either direction, and is of nearly equal strength whether on "edge" or on "bed." The formation is generally about forty feet in thickness, and presents a solid face, from which the quarryman may choose his dimensions unrestricted by any conditions save his ability to handle and transport the blocks. The Egyptian obelisk or the mighty stones of Baalbec could be readily surpassed in these quarries.

The Indiana Geological Report for 1878 gives analyses of samples from different quarries along the out-crop of the formation, from White river, in Owen county, to the Ohio river in Harrison county, showing a remarkable uniformity in its composition. All the samples show from 95 to 98 per cent. carbonate of lime, which is indestructible by ordinary atmospheric influences; while ferric oxide and alumina, to which most perishable stones owe their failure, occur here only from 0.34 to 1.00 per cent. This is a degree of purity rarely found.

In so far as durability can be inferred from chemical analysis, the oolitic limestone gives every assurance of permanence, which is further attested by the perpendicular and unworn aspect of all exposed faces along the out-crop and by its retention of tool-marks after forty years of exposure in buildings. It is only slightly absorbent of moisture; is perfectly free from saltpeter or other eflorescent salts; and its high degree of elasticity enables it to resist, without injury, the otherwise destructive effects of freezing the absorbed moisture, and of unequal expansion or contraction from sudden and unequal changes of temperature.

Its rich grey color, close and uniform texture, and facility of working, both by hand and by machinery, make it extremely valuable for architectural purposes, and its assured strength and durability make it especially desirable for all permanent engineering works. When it has become better known and appreciated abroad, it will form a prominent item in the commerce of the State. It is already beginning to find its way to eastern markets, and the recent use of it in Mr. Vanderbilt's new residence in New York city, will serve to show eastern architects its many excellencies.

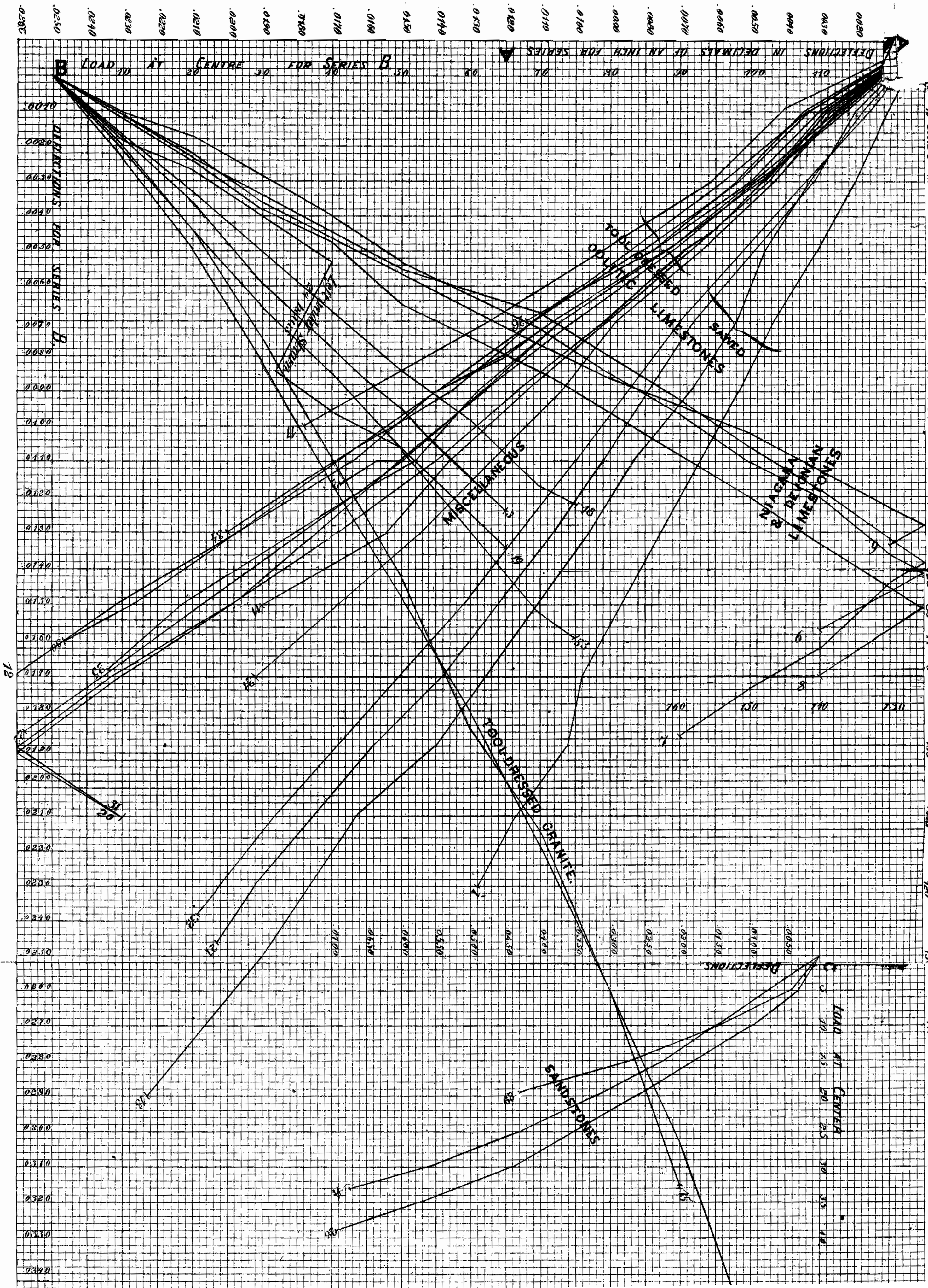

DIAGRAM SHOWING RESULTS OF EXPERIMENTS ON TRANSVERSE STRENGTH AND ELASTICITY OF BUILDING STONES

EXPERIMENTS ON THE TRANSVERSE STRENGTH AND ELASTICITY OF BU

NOTE.—All experiments in this series were upon a length of 14 inches between supports, and all "on bed" except where ot

FIRST GROUP—OOLITIC LIMESTONES, TOOL-DRESSED.

No. of Experiments.	QUARRY.		Resonance.	DIMENSIONS.		LOADS APPLIED.																		
						10 Lbs.		20 Lbs.		30 Lbs.		40 Lbs.		50 Lbs.		60 Lbs.		70 Lbs.		80 Lbs.		90 Lbs.		100 L
	Name.	Place.		b., Inches.	d., Inches.	Deflections Observed.	Deflections Corrected.	Deflections Observed.	Deflections Corrected.	Deflections Observed.	Deflections Corrected.	Deflections Observed.	Deflections Corrected.	Deflections Observed.	Deflections Corrected.	Deflections Observed.	Deflections Corrected.	Deflections Observed.	Deflections Corrected.	Deflections Observed.	Deflections Corrected.	Deflections Observed.	Deflections Corrected.	Deflections Observed.
2	Dark Hollow	Bedford, Indiana	Impaired	1.00	1.00	.0021	.0021	.0049	.0049	.0073	.0073	.0101	.0101	.0125	.0125	.0151	.0151	. . .	. . .	. . .	. . .	. . .	. . .	. . .
34	Dark Hollow	Bedford, Indiana	Impaired	1.00	0.98	.0035	.0033	.0062	.0058	.0090	.0085	.0118	.0111	.0145	.0136	.0180	.0169	.0213	.0200	. . .	. . .	. . .	. . .	. . .
11	Hege & Jackson	Near Spencer, Indiana	Impaired	0.90	1.07	.0026	.0029	.0042	.0046	.0060	.0066	.0082	.0090	.0104	.0114	.0123	.0136	.0140	.0154	.0172	.0190	. . .	. . .	. . .
25	Hege & Jackson	Near Spencer, Indiana	Impaired	1.06	1.08	.0018	.0024	.0035	.0047	.0055	.0074	.0079	.0106	.0096	.0128	.0110	.0147	.0136	.0182	.0159	.0212	. . .	. . .	. . .
12	Simpson & Archer	Near Spencer, Indiana	Impaired	1.12	1.18	.0018	.0033	.0029	.0054	.0044	.0081	.0061	.0112	.0076	.0140	.0091	.0168	.0107	.0197	.0126	.0232	. . .	. . .	. . .
24	Simpson & Archer	Near Spencer, Indiana	Impaired	1.13	1.08	.0017	.0025	.0030	.0043	.0045	.0064	.0062	.0088	.0073	.0104	.0087	.0124	.0102	.0145	.0118	.0168	.0135	.0192	. . .
17	Dunn & Co., Baalbec Quarry	Near Bedford, Indiana	Impaired	1.03	1.00	.0041	.0042	.0060	.0062	.0090	.0093	.0122	.0126	.0156	.0161	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
26	Dunn & Co., Baalbec Quarry	Near Bedford, Indiana	Impaired	0.98	0.95	.0036	.0030	.0060	.0050	.0093	.0078	.0134	.0112	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
20	E. R. Bladen	Near Spencer, Indiana	Impaired	1.05	1.07	.0022	.0028	.0034	.0044	.0052	.0067	.0071	.0091	.0091	.0117	.0109	.0140	.0130	.0168	.0153	.0197	.0179	.0230	.0200
22	E. R. Bladen	Near Spencer, Indiana	Impaired	1.05	1.06	.0021	.0026	.0038	.0048	.0059	.0074	.0083	.0104	.0102	.0128	.0120	.0150	.0143	.0179	.0166	.0208	.0188	.0235	. . .
30	J. Glover	Near Bedford, Indiana	Impaired	1.06	1.06	.0018	.0023	.0038	.0048	.0060	.0076	.0084	.0107	.0110	.0140	.0131	.0165	.0155	.0197	.0180	.0227	. . .	. . .	. . .
31	J. Glover	Near Bedford, Indiana	Impaired	1.10	1.07	.0025	.0034	.0040	.0054	.0058	.0078	.0077	.0104	.0094	.0127	.0112	.0151	.0130	.0176	.0147	.0198	.0172	.0232	.0192
	Averages	. . .	. . .	. . .	. . .	. . .	.0029	. . .	.0050	. . .	.0076	. . .	.0104	. . .	.0129	. . .	.0150	. . .	.0178	. . .	.0204	. . .	.0222	. . .

SECOND GROUP—OOLITIC LIMESTONES, SAWED.

No. of Experiments.	Name.	Place.	Resonance.	b., Inches.	d., Inches.	10 Lbs. Deflections Observed.	10 Lbs. Deflections Corrected.	20 Lbs. Deflections Observed.	20 Lbs. Deflections Corrected.	30 Lbs. Deflections Observed.	30 Lbs. Deflections Corrected.	40 Lbs. Deflections Observed.	40 Lbs. Deflections Corrected.	50 Lbs. Deflections Observed.	50 Lbs. Deflections Corrected.	60 Lbs. Deflections Observed.	60 Lbs. Deflections Corrected.	70 Lbs. Deflections Observed.	70 Lbs. Deflections Corrected.	80 Lbs. Deflections Observed.	80 Lbs. Deflections Corrected.	90 Lbs. Deflections Observed.	90 Lbs. Deflections Corrected.	100 L Deflections Observed.
1	John Matthews & Son.	Ellettsville, Indiana	Very Clear.	1.06	1.03	.0009	.0011	.0017	.0020	.0026	.0031	.0037	.0044	.0045	.0053	.0053	.0062	. . .	. . .	. . .	. . .	.0084	.0098	.0087
32	John Matthews & Son.	Ellettsville, Indiana	Very Clear.	1.06	1.06	.0013	.0016	.0027	.0034	.0041	.0051	.0055	.0070	.0067	.0085	.0079	.0100	.0093	.0117	.0105	.0132	.0118	.0159	.0133
13	D. Johnson	Bedford, Indiana	Clear.	1.07	1.07	.0015	.0020	.0025	.0033	.0035	.0046	.0041	.0054	.0051	.0067	.0063	.0083	.0073	.0096	.0085	.0111	.0096	.0126	.0107
21	D. Johnson	Bedford, Indiana	Clear.	1.07	1.04	.0017	.0020	.0027	.0032	.0041	.0049	.0054	.0066	.0066	.0079	.0077	.0092	.0090	.0107	.0103	.0123	.0116	.0138	.0132
	Averages	. . .	. . .	. . .	. . .	. . .	.0017	. . .	.0030	. . .	.0044	. . .	.0058	. . .	.0070	. . .	.0084	. . .	.0107	. . .	.0122	. . .	.0130	. . .

THIRD GROUP—OOLITIC LIMESTONES, MISCELLANEOUS.

No. of Experiments.	Name.	Place.	Resonance.	b., Inches.	d., Inches.	10 Lbs. Deflections Observed.	10 Lbs. Deflections Corrected.	20 Lbs. Deflections Observed.	20 Lbs. Deflections Corrected.	30 Lbs. Deflections Observed.	30 Lbs. Deflections Corrected.	40 Lbs. Deflections Observed.	40 Lbs. Deflections Corrected.	50 Lbs. Deflections Observed.	50 Lbs. Deflections Corrected.	60 Lbs. Deflections Observed.	60 Lbs. Deflections Corrected.	70 Lbs. Deflections Observed.	70 Lbs. Deflections Corrected.	80 Lbs. Deflections Observed.	80 Lbs. Deflections Corrected.	90 Lbs. Deflections Observed.	90 Lbs. Deflections Corrected.	100 L Deflections Observed.
18	Dunn & Co	Bloomington, Indiana	Good.	1.00	1.00	.0018	.0018	.0033	.0033	.0050	.0050	.0067	.0067	.0084	.0084	.0098	.0098	.0117	.0117	. . .	. . .	. . .	. . .	. . .
19	Dunn & Co	Bloomington, Indiana	Good.	1.03	0.97	.0020	.0019	.0029	.0027	.0042	.0040	.0056	.0053	.0114	.0107	.0133	.0125	. . .	. . .	. . .	. . .	. . .	. . .	. . .
3	Chicago & Bedford Stone Co	Bedford, Indiana	Clear.	1.01	1.04	.0017	.0019	.0031	.0035	.0053	.0060	.0068	.0077	.0084	.0095	.0102	.0116	. . .	. . .	. . .	. . .	. . .	. . .	. . .
33	Chicago & Bedford Stone Co	Bedford, Indiana	Clear	1.03	1.06	.0017	.0021	.0036	.0044	.0054	.0066	.0069	.0085	.0087	.0107	.0106	.0130	.0124	.0152	. . .	. . .	. . .	. . .	. . .

FOURTH GROUP—NIAGARA AND DEVONIAN LIMESTONES, SAWED.

No. of Experiments.	Name.	Place.	Resonance.	b., Inches.	d., Inches.	10 Lbs. Deflections Observed.	10 Lbs. Deflections Corrected.	20 Lbs. Deflections Observed.	20 Lbs. Deflections Corrected.	30 Lbs. Deflections Observed.	30 Lbs. Deflections Corrected.	40 Lbs. Deflections Observed.	40 Lbs. Deflections Corrected.	50 Lbs. Deflections Observed.	50 Lbs. Deflections Corrected.	60 Lbs. Deflections Observed.	60 Lbs. Deflections Corrected.	70 Lbs. Deflections Observed.	70 Lbs. Deflections Corrected.	80 Lbs. Deflections Observed.	80 Lbs. Deflections Corrected.	90 Lbs. Deflections Observed.	90 Lbs. Deflections Corrected.	100 L Deflections Observed.
6	Niagara	Greensburg, Indiana	Clear	0.98	1.02	.0011	.0011	.0018	.0019	.0028	.0029	.0039	.0041	.0051	.0053	.0063	.0066	.0073	.0076	.0082	.0085	.0092	.0096	.0106
8	Niagara	Greensburg, Indiana	Clear	1.02	0.99	.0012	.0012	.0024	.0024	.0038	.0038	.0048	.0048	.0066	.0065	.0076	.0075	.0086	.0085	.0098	.0097	.0110	.0109	.0121
7	Devonian	North Vernon, Indiana	Clear	1.03	1.03	.0010	.0011	.0021	.0024	.0030	.0034	.0039	.0044	.0047	.0054	.0054	.0061	.0061	.0068	.0071	.0080	.0082	.0092	.0095
9	Devonian	North Vernon, Indiana	Clear	1.03	1.03	.0010	.0011	.0020	.0023	.0032	.0036	.0041	.0046	.0051	.0057	.0060	.0067	.0069	.0078	.0077	.0087	.0083	.0093	.0090
	Averages	. . .	. . .	. . .	. . .	. . .	.0011	. . .	.0022	. . .	.0034	. . .	.0045	. . .	.0057	. . .	.0067	. . .	.0077	. . .	.0087	. . .	.0098	. . .

FIFTH GROUP—GRANITE, TOOL-DRESSED.

No. of Experiments.	Name.	Place.	Resonance.	b., Inches.	d., Inches.	10 Lbs. Deflections Observed.	10 Lbs. Deflections Corrected.	20 Lbs. Deflections Observed.	20 Lbs. Deflections Corrected.	30 Lbs. Deflections Observed.	30 Lbs. Deflections Corrected.	40 Lbs. Deflections Observed.	40 Lbs. Deflections Corrected.	50 Lbs. Deflections Observed.	50 Lbs. Deflections Corrected.	60 Lbs. Deflections Observed.	60 Lbs. Deflections Corrected.	70 Lbs. Deflections Observed.	70 Lbs. Deflections Corrected.	80 Lbs. Deflections Observed.	80 Lbs. Deflections Corrected.	90 Lbs. Deflections Observed.	90 Lbs. Deflections Corrected.	100 L Deflections Observed.
15	Hallowell Granite.	H. D. G. Co., New York	Very Dull.	1.00	1.04	.0018	.0020	.0039	.0044	.0066	.0075	.0098	.0110	.0126	.0142	.0165	.0186	.0191	.0215	.0231	.0260	.0280	.0315	. . .
23	Hallowell Granite.	H. D. G. Co., New York	Very Dull.	1.04	1.06	.0018	.0023	.0040	.0050	.0066	.0082	.0094	.0117	.0120	.0149	.0146	.0181	.0177	.0219	.0210	.0260	.0245	.0304	. . .
	Averages	. . .	. . .	. . .	. . .	. . .	.0022	. . .	.0047	. . .	.0078	. . .	.0113	. . .	.0146	. . .	.0184	. . .	.0217	. . .	.0260	. . .	.0309	. . .

SIXTH GROUP—SANDSTONES, SAWED.

No. of Experiments.	Name.	Place.	Resonance.	b., Inches.	d., Inches.	5 Lbs. Deflections Observed.	5 Lbs. Deflections Corrected.	10 Lbs. Deflections Observed.	10 Lbs. Deflections Corrected.	15 Lbs. Deflections Observed.	15 Lbs. Deflections Corrected.	20 Lbs. Deflections Observed.	20 Lbs. Deflections Corrected.	25 Lbs. Deflections Observed.	25 Lbs. Deflections Corrected.	30 Lbs. Deflections Observed.	30 Lbs. Deflections Corrected.	35 Lbs. Deflections Observed.	35 Lbs. Deflections Corrected.	40 Lbs. Deflections Observed.	40 Lbs. Deflections Corrected.	45 Lbs. Deflections Observed.	45 Lbs. Deflections Corrected.	50 L Deflections Observed.
4	. . .	Grafton, Ohio	None	1.03	1.00	. . .	. . .	.0280	.0288	.0439	.0462	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
5	. . .	Grafton, Ohio	None	1.03	1.00	. . .	. . .	.0022	.0288	. . .	. . .	.0042	.0550	. . .	. . .	.0069	.0903	. . .	. . .	. . .	. . .	. . .	. . .	. . .
29	. . .	Grafton, Ohio	None	1.00	1.00	.0040	.0040	.0140	.0140	.0270	.0270	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
14	Halderman	Berea, Ohio	None	1.08	1.03	. . .	. . .	.0123	.0145	.0193	.0228	.0270	.0318	.0364	.0430	.0468	.0560	. . .	. . .	. . .	. . .	. . .	. . .	. . .
28	Halderman	Berea, Ohio	None	1.07	1.03	.0028	.0033	.0082	.0096	.0153	.0179	.0220	.0257	.0290	.0339	.0375	.0438	.0483	.0565	. . .	. . .	. . .	. . .	. . .
	Averages	. . .	. . .	. . .	. . .	. . .	.0036	. . .	.0196	. . .	.0285	. . .	.0375	. . .	.0385	. . .	.0633	. . .	.0565	. . .	. . .	. . .	. . .	. . .

No. 2.—At 20 lbs. no permanent set; at 60 lbs. permanent set, .0028.
No. 25.—Deflection at instant of rupture, observed .0175; corrected .0234.
No. 22.—Deflection at instant of rupture, observed .0206; corrected .0258.
No. 30.—Deflection at instant of rupture, observed .0195; corrected .0247. At 60 lbs. no permanent set.
No. 32.—Deflection at instant of rupture, observed .0166; corrected .0209.

No. 21.—Deflection at instant of rupture, observed .0170; corrected .0203.
*Average, Second Group.—Crushing strength, average of five of Gilmore's tests, not identical with these quarries, but known to have been sawed.
Nos. 18 and 19.—Mode of working unknown, probably sawed, and No. 18 wrongly marked for "bed," and therefore tested on edge.

No. 19.—At 40 lbs. left under strain twenty-four
tion increased from .0056 to .0090, and strain r
On restoring strain to 40 lbs. deflection becam
Nos. 3 and 33.—Sawed with quarry beds at right a
No. 6.—At 70 lbs. permanent set .0006; on bed.
No. 8.—At 60 lbs. no permanent set; on edge.

ILDING STONES.

herwise noted.

lbs.	110 Lbs.		120 Lbs.		130 Lbs.		140 Lbs.		150 Lbs.		160 Lbs.		Load Causing Rupture—Pounds.	Modulus of Rupture.	Modulus of Elasticity.	Resistance to Crushing—(Gilmore.)
Deflections Corrected.	Deflections Observed.	Deflections Corrected.	Deflections Observed.	Deflections Corrected.	Deflections Observed.	Deflections Corrected.	Deflections Observed.	Deflections Corrected.	Deflections Observed.	Deflections Corrected.	Deflections Observed.	Deflections Corrected.				
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	66	1,386	2,834,400	6,625
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	70	1,530	2,391,000	6,750
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	80	1,630	2,952,500	8,750
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	88	1,490	2,738,300	. . . .
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	90	1,212	2,463,750	7,500
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	90	1,434	3,184,500	8,750
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	55	1,121	2,062,000	6.500
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	40	950	2,553,750	. . . .
.0258	.0225	.0290	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	110	1,928	2,930,000	. . . .
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	98	1,744	2,693,500	. . . .
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	85	1,500	2,669,000	10,125
.0259	.0215	.0290	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	110	1,800	2.681,000	. . . .
.0259	. . .	.0290	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	1,477	2,679,475	7,857
.0102	.0100	.0117	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	120	2,240	6,494,000	13,500
.0168	.0148	.0187	.0161	.0203	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	124	2,187	4,083,800	. . . .
.0140	.0124	.0163	.0134	.0176	.0145	.0190	.0158	.0207	.0170	.0223	. . .	. . .	150	2,593	4,691,670	. . . .
.0158	.0146	.0175	.0161	.0192	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	128	2,331	4,288,460	. . . .
.0142	. . .	.0160	. . .	.0190	. . .	.0190	. . .	.0207	. . .	.0223	. . .	. . .	. . .	2,338	4,889,480	*12,675
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	75	1,575	4,101,250	13,750
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	65	1,408	4,763,750	. . . .
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	65	1,478	3,590,000	11,750
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	75	1,361	3,180,000	. . . .
.0110	.0116	.0120	.0131	.0136	.0141	.0146	.0151	.0157	. . .	. . .	. . .	. . .	140	2,785	6,800,000	16,875
.0120	.0134	.0133	.0147	.0145	.0159	.0157	.0171	.0169	. . .	. . .	. . .	. . .	140	2,940	5,650,000	. . . .
.0107	.0105	.0118	.0117	.0132	.0128	.0144	.0144	.0162	.0154	.0173	.0166	.0187	160	3,075	6,350,000	15,750
.0101	.0101	.0114	.0110	.0124	.0118	.0133	. . .	. . .	. . .	. . .	. . .	. . .	130	2,499	6,400,000	. . . .
.0112	. . .	.0121	. . .	.0134	. . .	.0145	. . .	.0163	. . .	.0173	. . .	.0187	. . .	2,825	6,300,000	16,312
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	90	1,748	2,527,800	. . . .
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	98	1,761	2,495,800	. . . .
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . . . . .	. . . .
bs.																
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	18	367	232,500	. . .
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	37	323	246,670	. . .
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	19	399	507,500	. . .
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	33	587	417,000	. . .
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	39	721	587,500	. . .
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	479	398,234	. . .

hours, and found deflec-
educed from 40 to 34 lbs.
e .0097.
ngles to axis of bar.

No. 7.—At 60 lbs. no permanent set; on bed.
No. 9.—At 60 lbs. no permanent set; on edge.
No. 4.—At 10 lbs. permanent set .0045.
No. 5.—Length between supports six inches. This was one of the broken pieces of No. 4.
No. 14.—At 20 lbs. permanent set .0080.