Highway Materials Research Laboratory
132 Graham Avenue, Lexington 29, Ky.
October 27, 1947

File: A-1-6
Res. Proj. C-22

Memo. to Dean Terrell,
Director of Research

At the meeting of the Research Board on March 24, we presented our first Progress Report on Project C-22, entitled "A Study of the "Properties of Coarse Aggregates", and at that time an oral discussion was given by Mr. James L. Young, Jr., Assistant Research Engineer, in the capacity of geologist for our laboratory. Work on this project since March 24 has made possible a second Report of Progress on this study, a copy of which is attached.

You will recall that the original plan for this investigation included very extensive tests for chemical and mineralogical properties for limestone from four widely separated and different quarries. These were sampled at one foot intervals and during inspection of the laboratory last November 25, Mr. Young gave an account of his sampling, the laboratory techniques developed to that date, and the objectives of the research so far as they could be formulated at that time. It is gratifying to note that at the present stage a very large majority of chemical and mineralogical properties have been determined for all four of the quarries, and many samples have been prepared for the purpose of correlating these properties of the limestone with performance in concrete and bituminous mixes.

In line with our policy heretofore Mr. Young and Mr. James H. Havens, Jr. Materials Engineer and Chemist in our laboratory, will give an oral presentation of this voluminous report in order to condense and interpret the data.

Respectfully submitted

L. E. Gregg
L. E. Gregg
Associate Director of Research

LG:K

cc: Members of the
Research Board

Commonwealth of Kentucky
Department of Highways

Progress Report No. 2
on
Research Project C-22

A STUDY OF THE PROPERTIES OF COARSE AGGREGATES

by

James L. Young, Jr.
Assistant Research Engineer

and

James H. Havens
Junior Materials Engineer

Highway Materials Research Laboratory
Lexington, Kentucky

October, 1947

OUTLINE

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Research Project C-22 is an investigation of the geologic aspects of limestone aggregate that might cause failure if used in highway construction, as reported earlier. As the study was to be approached from a new standpoint, it was allowed to mature along significant lines. At present a working plan has been adopted and is shown here in some detail.

Four quarries were selected on the basis of performance of the aggregates in pavements. The four selected, together with their rating, were:

(<u>Fair</u>)	Quarry No. 1 -	Composed of 31 feet of Ordovician limestone. Location - Lexington.
(<u>Good</u>)	Quarry No. 2 -	Composed of 134 feet of Mississippian limestone. Location - Mt. Vernon.
(<u>Poor</u>)	Quarry No. 3 -	Composed of 65 feet of Mississippian limestone. Location - Olive Hill.
(<u>Excellent</u>)	Quarry No. 4 -	Composed of 35 feet of Silurian dolomite. Location - Avoca.

These quarries have been collected and tested in detail until a very sound idea of all their physical properties, their variations, structure, mineralogy, etc. is known. By results of present tests it is possible to locate a random sample very closely in the quarry and in most cases orient it.

As the evaluations placed on these quarries can at best be only general, physical tests were selected with which to evaluate the aggregate closer and thereby to correlate an aggregate's performance accurately with the results of significant tests performed on it. First, it is necessary to prove that one property or a series of properties combined cause the failure.

The quarries are collected a second time with a new purpose. Four to eight levels have been selected at which point one or more properties is outstanding: A large sample is selected 2' x 3½' x 1'. From it, six beams are sawed on a carborundum masonry saw, and the remaining rock is crushed to furnish the aggregate for other physical tests and approximately six concrete beams. These beams are to be subjected to the following physical and chemical tests to determine performance and to correlate it with physical properties measured by old tests as well as by those that are new.

1. Insoluble Residue
2. Permeability
3. Porosity
4. Bulk Specific Gravity
5. Absolute Specific Gravity
6. Thin Section
7. Size, Shape and Frequency of Pores
8. Clay Minerals
9. Los Angeles Abrasion
10. Sodium Sulfate Soundness
11. Sonic Modulus of Elasticity (rock beam)
12. Modulus of Rupture (rock beam)
13. Durability Index (rock beam)
14. Sonic Modulus of Elasticity (concrete beam)
15. Modulus of Rupture (concrete beam)
16. Durability Index (concrete beam)
17. Coefficient of Thermal Expansion.
18. Toughness
19. Hardness
20. Ductility by Compression Tests

A sample form is included on the next page to show what control may be expected in dealing with this size beam.

H.R.L. Form G-1

Commonwealth of Kentucky
Department of Highways

Highway Materials Research Laboratory

REPORT OF IMPROMPTU TESTS

File: R-2

Date: 8-11-47

Subject: Variations in Insoluble Residue over a Beam 2 inches x 3 inches x 12 inches

Location Sampled: Central Rock Surface

Date Sampled: July 26 Sampled By: T. Wolfe

Reason for Sampling (related work, etc.): To determine what control may be expected in testing beams in Research Project C-22

Results: Samples A - 1.16% (22A)

B - 1.20% (22B)

C - 1.20% (22C)

D - .90% (22D)

(All from one beam at 22 ft. level.)

Remarks: Samples taken from four areas in longest dimension of beam after it was broken. Maximum deviation is 0.3%.

Reported By: J. Young & J. Havens

Copies: Gregg
Havens
Young
File

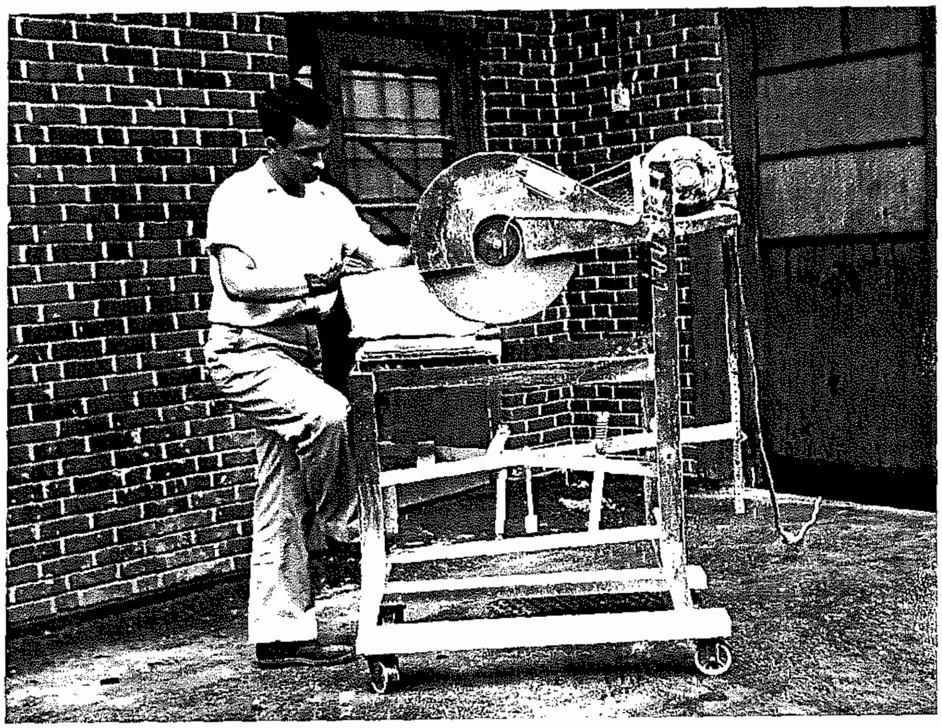


Figure 1. Beams of Limestone Being Sawed on a Carborundum Masonry Saw

RESULTS

At the time of the last Research Board Meeting, tests and results were partially completed, and reported as such. At this time tests are more fully completed and will be reported with as much detail toward results as the progress allows.

Insoluble Residue

That portion of a limestone which refuses to go into solution upon digestion in a fairly active acid is termed the insoluble residue. It has been postulated that the insoluble residue should be a proper criterion in diagnosing the behavior of an aggregate. This seems to be true, and is the only test found to date that is discriminating.

Digestion is carried on at room temperature with one exception. Quarry No. 4 is dolomitic and the magnesium carbonate is more stable than calcium carbonate. In order to get the magnesium carbonate into complete solution, heating to just below boiling is necessary.

Formation of insoluble chlorides is a detrimental phenomena but is considered to be a negligible error. Silicates go into solution to such a small extent in hydrochloric acid that they are not considered.

Quarry Averages are the only criterion available for evaluation of a quarry as a whole and the averages place the quarries nearly in line with reference to the initial general performance ratings given to these quarries.

INSOLUBLE RESIDUE

QUARRY NO. 1, LEXINGTON, KY.

Level	Insol. Res.
0	10.5%
1	8.5%
2	6.5%
3	10.0%
4	10.0%
5	8.0%
6	3.0%
7	1.0%
8	1.0%
9	3.0%
10	4.0%
11	5.0%
12	2.5%
13	2.0%
14	4.5%
15	3.5%
16	4.0%
17	6.5%
18	6.0%
19	5.0%
20	2.5%
21	2.5%
22	6.5%
23	4.5%
24	2.5%
25	8.5%
26	5.5%
27	6.5%
28	6.5%
29	3.5%
30	6.0%
Quarry Average -	5.145%

INSOLUBLE RESIDUE

QUARRY NO. 2, MOUNT VERNON, KY.

Level	Insol. Res.	Level	Insol. Res.
1	1.5%	51	2.0%
2	4.0%	52	2.5%
3	5.0%	53	2.5%
4	7.5%	54	2.5%
5	4.5%	55	4.5%
6	3.5%	56	5.0%
7	2.5%	57	2.5%
8	0.5%	58	6.5%
9	2.0%	59	2.5%
10	1.0%	60	5.0%
11	1.0%	61	1.0%
12	0.5%	62	8.5%
13	1.0%	63	4.0%
14	1.0%	64	2.0%
15	1.0%	65	1.0%
16	3.0%	66	1.0%
17	6.0%	67	1.0%
18	8.0%	68	1.5%
19	7.0%	69	2.0%
20	6.5%	70	2.0%
21	4.0%	71	2.0%
22	8.0%	72	4.0%
23	3.0%	73	Covered
24	3.0%	74	2.5%
25	1.5%	75	1.0%
26	3.0%	76	2.0%
27	4.0%	77	1.0%
28	2.5%	78	0.5%
29	6.5%	79	1.0%
30	3.5%	80	3.0%
31	2.5%	81	2.5%
32	3.5%	82	3.0%
33	17.5%	83	6.0%
34	Shale	84	10.5%
35	6.5%	85	12.0%
36	5.5%	86	10.0%
37	4.5%	87	5.5%
38	3.0%	88	3.0%
39	3.5%	89	5.5%
40	2.5%	90	7.0%
41	3.0%	91	4.5%
42	3.0%	92	5.0%
43	5.0%	93	3.5%
44	3.5%	94	4.5%
45	5.5%	95	7.0%
46	6.5%	96	8.0%
47	10.0%	97	3.0%
48	5.5%	98	3.5%
49	7.5%	99	3.5%
50	8.0%	100	3.0%

QUARRY NO. 2 (Continued)

Level	Insol. Res.
101	5.0%
102	3.0%
103	2.5%
104	2.0%
105	3.5%
106	3.5%
107	1.5%
108	2.0%
109	1.0%
110	3.0%
111	Covered
112	5.5%
113	2.5%
114	1.5%
115	2.5%
116	1.5%
117	2.0%
118	10.0%
119	3.0%
120	3.5%
121	2.5%
122	4.0%
123	3.0%
124	2.5%
125	2.5%
126	5.0%
127	3.0%
128	4.0%
129	2.0%
130	5.5%
131	6.0%
132	Covered
133	7.0%
134	4.0%
135	5.5%
Quarry Average	3.88%

INSOLUBLE RESIDUE

QUARRY NO. 3, OLIVE HILL, KY.

Level	Insol. Res.	Level	Insol. Res.
1	12.5%	34	26.5%
2	9.5%	35	25.5%
3	10.5%	36	16.0%
4	12.5%	37	11.5%
5	14.5%	38	8.5%
6	9.0%	39	8.0%
7	4.5%	40	7.0%
8	20.0%	41	10.0%
9	15.0%	42	4.5%
10	11.0%	43	17.5%
11	13.0%	44	19.5%
12	19.5%	45	20.0%
13	12.0%	46	16.0%
14	8.5%	47	17.0%
15	9.0%	48	20.5%
16	14.5%	49	11.5%
17	7.5%	50	14.0%
18	11.5%	51	9.5%
19	59.5%	52	11.0%
20	28.0%	53	4.0%
21	Shale	54	10.5%
22	14.0%	55	6.5%
23	20.0%	56	4.0%
24	13.0%	57	8.0%
25	4.5%	58	4.5%
26	6.0%	59	4.0%
27	11.5%	60	5.0%
28	14.0%	61	3.0%
29	13.5%	62	1.5%
30	11.0%	63	2.0%
31	6.0%	64	2.5%
32	7.5%	65	1.5%
33	8.5%	Quarry Average	-11.9%

INSOLUBLE RESIDUE

QUARRY NO. 4, AVOCA, KY.

Level	Insol. Res.
1	8.26%
2	4.50%
3	3.73%
4	10.38%
5	3.25%
6	1.91%
7	3.15%
8	1.37%
9	1.05%
10	1.13%
11	1.31%
12	1.35%
13	3.04%
14	1.43%
15	1.97%
16	2.75%
17	2.59%
18	2.39%
19	1.32%
20	1.71%
21	--
22	5.32%
23	5.54%
24	3.49%
25	7.05%
26	7.66%
27	7.52%
28	6.12%
29	6.51%
30	7.00%
31	5.78%
32	5.77%
33	6.97%
Quarry Average	4.166%

Permeability

The permeability of a solid may be defined as the rate of flow of a given fluid through a unit cross section of the solid under a unit pressure gradient and conditions of viscous flow; permeability is therefore a measure of fluid conductivity of a solid. The standard unit of permeability as defined by the American Petroleum Institute (tentatively) is the "darcy", which is the rate of flow in milliliters per second, of a fluid of one centipoise viscosity through a cross section of one square centimeter of a porous medium, under a pressure gradient of one atmosphere (76.0 cm. Hg.) per centimeter and conditions of viscous flow.

Permeable mediums are necessarily porous but porous need not be permeable. The connections of the pore spaces included in a medium determine its permeability. Limestone has a very low permeability, as a rule, when compared to a reservoir rock such as an oil sand. However, small as the openings are, a limestone is usually quarried out fully saturated with water. This means then in the role of an aggregate in concrete pavements, the voids may be utilized in any exchange of water taking place. The total amount of hygroscopic water present in most cases will not exceed one per cent, but the influence of this small per cent cannot be ignored. If the size openings fall within the capillary limits, an unestimable force is brought into action. Such might be the case with Quarry No. 3 which had very low permeability as measured by the method adopted.

Specimens were cored out with a diamond studded core drill.

core used was 1.7 centimeters in diameter by 2.7 centimeters length, presenting a 2.27 square centimeter face to the testing ium.

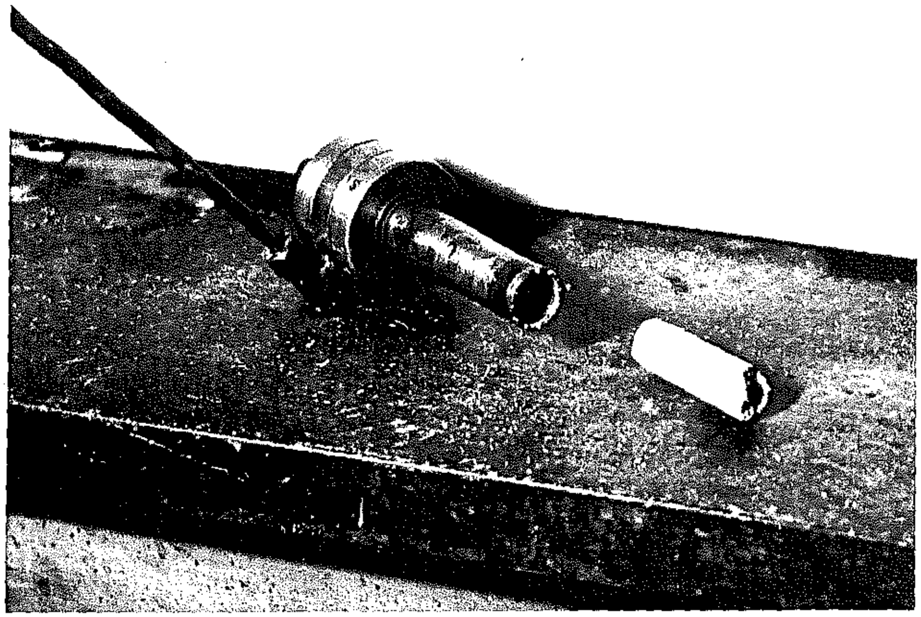


Fig. 2. Diamond Core Drill and Limestone Core

The sample was mounted in a simple adaptation of equipment lescribed by Wycoff, Botset, Muscat and Reed in the February, 1934 oulletin of the American Association of Petroleum Geologists. The nedium used was compressed, dried air. The sample was mounted in rubber gasket, subjected to a known pressure and temperature and he air passing through the specimen was trapped in a calibrated lass tube. The computations are in "millidarcies" or one one housandth of a "darcy". Two directions were tested from each evel. The formula is shown:

$$= \frac{2000 \times l. \times \text{viscosity of air} \times \text{vol. of air}}{\text{area in sq. cm.} \times \text{difference in pressure}} = \_\_\_ \text{ Millidarcies}$$

RESULTS OF PERMEABILITY IN MILLIDARCYS

QUARRY NO. 1, CENTRAL ROCK COMPANY, LEXINGTON, KY.

Level	Position of Sample Vert.	Hort.
0	.741	0.903
1	.463	1.160
2	2.000	.879
3	1.493	1.864
4	.625	.786
5	.417	2.512
6	1.094	1.967
7	3.422	1.059
8	1.700	.862
9	1.303	.827
10	.897	.485
11	.489	1.094
12	.256	.583
13	.384	.886
14	.373	.233
15	.419	.360
16	.129	.210
17	.484	.922
18	.265	.231
19	.553	.311
20	.507	.138
21	.196	.276
22	.553	.576
23	.369	.829
24	.150	.300
25	.289	.553
26	.174	.510
27	.417	.753
28	--	.382
29	.278	.406
30	.510	.463
Quarry Average	.6983	.7399

RESULTS OF PERMEABILITY IN MILLIDARCYS

QUARRY NO. 2, MOUNT VERNON, KY.

Level	Position of Sample Vert.	Position of Sample Hort.
1	0.000	0.000
2	0.000	0.000
3	0.000	0.000
4	0.000	0.000
5	0.000	0.000
6	0.000	0.000
7	0.000	--
8	0.000	0.000
9	0.593	0.000
10	66.480	21.928
11	1.941	9.079
12	293.300	188.550
13	0.265	0.000
14	0.000	0.000
15	0.000	0.000
16	0.000	0.000
17	0.000	0.000
18	0.000	0.000
19	--	--
20	0.000	0.000
21	0.000	0.000
22	0.000	0.000
23	0.000	0.000
24	0.000	0.000
25	0.000	0.000
26	0.000	0.000
27	0.000	0.000
28	0.000	0.000
29	0.000	0.000
30	0.000	0.000
31	0.000	0.000
32	0.000	0.000
33	0.000	0.000
34	0.000	0.000
35	0.000	0.000
36	0.000	0.000
37	0.000	0.000
38	0.000	0.000
39	0.000	0.000
40	0.000	0.000
41	0.000	0.000
42	0.000	0.000
43	0.000	0.000
44	0.000	0.000
45	0.000	0.000
46	0.000	0.000
47	0.000	0.000
48	0.000	0.000
49	0.000	0.000
50	0.000	0.000

Level	Position of Sample Vert.	Position of Sample Hort.
51	0.000	0.000
52	0.000	0.000
53	0.000	0.000
54	--	--
55	0.000	0.000
56	0.000	0.000
57	0.000	--
58	0.000	0.000
59	0.000	0.000
60	0.000	0.000
61	--	--
62	--	--
63	0.139	0.097
64	--	--
65	0.056	0.111
66	0.042	0.011
67	0.000	0.000
68	0.000	0.000
69	0.000	0.005
70	0.000	0.000
71	0.000	0.000
72	0.000	0.000
73	0.000	0.000
74	0.000	0.000
75	0.000	0.000
76	0.000	0.000
77	0.000	0.000
78	0.000	0.000
79	0.000	0.000
80	0.000	0.000
81	0.000	0.000
82	--	--
83	--	--
84	0.000	0.000
85	0.111	0.028
86	0.000	0.000
87	--	--
88	0.000	0.000
89	0.000	0.000
90	0.000	0.000
91	0.000	0.000
92	0.000	0.000
93	0.000	0.000
94	0.000	0.000
95	0.154	0.028
96	--	--
97	0.000	0.000
98	0.000	0.000
99	0.000	0.000
100	0.098	0.000

QUARRY NO. 2 (Continued)

Level	Position of Sample Vert.	Position of Sample Hort.
101	0.000	0.000
102	0.000	0.000
103	0.000	0.000
104	0.000	0.000
105	--	--
106	0.391	0.000
107	0.000	0.000
108	0.000	0.000
109	0.000	0.000
110	0.000	0.000
111	0.000	0.000
112	0.000	0.000
113	0.139	0.000
114	0.000	0.000
115	0.000	0.000
116	0.000	0.000
117	0.000	0.000
118	0.000	0.000
119	0.000	0.000
120	0.000	0.000
121	0.000	0.000
122	0.000	0.000
123	0.000	0.000
124	0.000	0.000
125	0.000	0.000
126	0.000	0.000
127	0.000	0.000
128	0.000	0.000
129	0.000	0.000
130	0.000	0.000
131	0.000	0.000
132	--	--
133	0.000	0.000
134	0.000	0.000
135	0.000	0.000
Quarry Average	5.272	1.773

RESULTS OF PERMEABILITY IN MILLIDARCYS

QUARRY NO. 3, OLIVE HILL, KY.

Level	Position of Sample: Vert.	Position of Sample: Hort.
1	0.000	0.000
2	0.000	0.000
3	0.000	0.000
4	0.000	0.000
5	0.000	0.000
6	0.000	0.000
7	0.000	0.000
8	0.000	0.000
9	0.000	0.000
10	0.000	0.000
11	0.000	0.000
12	0.000	0.000
13	0.000	0.000
14	0.000	0.000
15	0.000	0.000
16	0.000	0.000
17	0.140	0.000
18	0.000	0.114
19	0.081	0.000
20	0.000	0.000
21	SEAM	--
22	0.292	0.760
23	0.421	0.632
24	1.100	1.100
25	0.000	--
26	0.000	0.000
27	0.529	0.682
28	1.165	1.176
29	1.117	1.741
30	0.988	1.024
31	0.400	0.882
32	0.717	1.176
33	0.894	1.211
34	0.000	0.000
35	0.000	0.000
36	0.000	0.000
37	0.000	0.000
38	0.000	0.000
39	0.000	0.000
40	0.000	0.000
41	0.000	0.000
42	0.000	0.000
43	0.000	0.000
44	0.000	0.000
45	0.000	0.000
46	0.000	0.000
47	0.000	0.000
48	0.000	0.047
49	0.000	0.000
50	0.000	0.047
51	0.000	0.000
52	0.000	0.000
53	0.000	0.000
54	0.000	0.000
55	0.000	0.000
56	0.000	0.000
57	0.000	0.000
58	0.081	0.000
59	0.000	0.000
60	0.000	0.000
61	0.046	0.000
62	0.000	0.000
63	0.000	0.000
64	0.000	0.000
65	0.046	0.000
Quarry Average	0.1233	0.163[illegible]

RESULTS OF PERMEABILITY IN MILLIDARCYS

QUARRY NO. 4, AVOCA, KY.

Level	Position of Sample: Vert.	Position of Sample: Hort.
0	0.386	0.327
1	0.397	0.410
2	0.222	0.152
3	0.281	0.468
4	0.937	.117
5	.235	.046
6	11.940	47.750
7	.316	.246
8	.117	.000
9	.000	.000
10	.000	.000
11	.282	.671
12	.047	.318
13	.483	.165
14	1.810	.282
15	.000	.000
16	.118	.130
17	.000	.095
18	.163	.046
19	.200	.163
20	.262	14.921
21	.338	6.670
22	3.043	28.297
23	.081	.081
24	.211	.163
25	.000	.046
26	.000	.000
27	.000	.000
28	.164	.000
29	.046	.000
30	.095	.000
31	.000	.000
32	.000	.000
33	2.824	1.024
Quarry Average	0.735	3.017

Hygroscopic Water and Carbon Dioxide

An experiment was run to determine if water content or CO_2 content is indicative enough to be characteristic of different phases of sedimentation.

If true, this would be a good criterion for establishing zones differing in sedimentation in any geologic column of calcareous rocks.

Procedure- (H_2O content) Six capsules are heated to 725° C. in a muffle furnace or to constant weight. They are placed in a oven and heated @ 100 - 105° C. for four hours or more. They are placed in a dessicator and allowed to cool to room temperature at which point they are weighed. About 2 grams of powdered limestone (passing 150 mesh) are placed in the capsules. They are weighed, put in an oven @ 100 - 105° C. and left for 12-14 hours. They are placed in a dessicator and allowed to cool to room temperature at which point they are weighed. Loss of weight is a measure of the water content of the rock and will be expressed as a percentage of the total weight of the sample. (CO_2 and organic matter) The samples are now placed in the muffle furnace, taken to 750° C. and left for four hours. At the conclusion of this time they are placed in a dessicator and brought to room temperature. The loss of weight is a direct measure of the CO_2 and organic matter combined.

For this experiment arbitrary zones assigned in Quarry No. 1 were utilized and samples taken from the material used in insoluble residue determination. Samples 1-5 are from the corresponding zone number. Sample 6 is taken from the 18 foot level Quarry No. 3.

Weights are indicated as follows:

A. Wt. of Crucibles at Constant Weight

No. 1 - 12.0314 gms.
No. 2 - 12.2219 "
No. 3 - 12.6611 "
No. 4 - 12.1040 "
No. 5 - 11.9056 "
No. 6 - 12.1969 "

B. Wt. of Crucibles at Constant Weight + Wt. of Crushed Ls. at Room Tep. & Humidity

2.1540 No. 1 - 14.1854 (Zone 1-Q-1)
1.7429 No. 2 - 13.9648 (Zone 2-Q-1)
1.8991 No. 3 - 14.5602 (Zone 3-Q-1)
1.7297 No. 4 - 13.8337 (Zone 4-Q-1)
1.9136 No. 5 - 13.8192 (Zone 5-Q-1)
2.5462 No. 6 - 14.7431 (18 ft. Olive Hill)

C. Wt. of Crucible + Sample after 14 hrs. at 100°C.

No. 1 - 14.1830 - .1114%
No. 2 - 13.9627 - .1205%
No. 3 - 14.5587 - .079%
No. 4 - 13.8341 - ?
No. 5 13.8199 - ?
No. 6 - 14.7412 - .0746%

D. Wt. of Crucible + Sample after 750°C. decomp.

No. 1 - 13.3222 gms.
No. 2 - 13.2877 "
No. 3 - 13.7866 "
No. 4 - 13.1514 "
No. 5 - 13.0431 "
No. 6 - 13.7487 "

This indicates -

No. 1 - 39.96% CO_2 + Org. Mat.
No. 2 - 38.72% " " "
No. 3 - 40.65% " " "
No. 4 - 39.65% " " "
No. 5 - 40.59% " " "
No. 6 - 38.97% " " "

With intent to check results on the first determination the same samples were run again under similar conditions. Results were as follows:

A. No. 1 - 13.5961 gms.
No. 2 - 19.3577 "
No. 3 - 17.3164 "
No. 4 - 15.5076 "
No. 5 - 16.2475 "
No. 6 - 19.0676 "

			Wt. of Ls. Sample
B.	No. 1 - 16.4499	gms.	- 2.8538 gms.
	No. 2 - 21.8909	"	- 2.5332 "
	No. 3 - 20.1121	"	- 2.7957 "
	No. 4 - 18.7636	"	- 3.2560 "
	No. 5 - 19.4851	"	- 3.2376 "
	No. 6 - 22.3581	"	- 3.2905 "

			Wt. of Water
C.	No. 1 - 16.4447	gms.	- .0052 gms.
	No. 2 - 21.8838	"	- .0071 "
	No. 3 - 20.1040	"	- .0081 "
	No. 4 - 18.7596	"	- .0040 "
	No. 5 - 19.4825	"	- .0026 "
	No. 6 - 22.3536	"	- .0045 "

In terms of percentage this indicates -

No. 1 - .182% of water
No. 2 - .280% "
No. 3 - .289% "
No. 4 - .122% "
No. 5 - .080% "
No. 6 - .136% "

D. No. 1 - 15.3030 gms.
No. 2 - 20.8976 "
No. 3 - 18.9708 "
No. 4 - 17.4890 "
No. 5 - 18.1571 "
No. 6 - 21.0636 "

This indicates -

No. 1 - 40.00% of CO_2 and Organic Matter
No. 2 - 39.45% " " " " "
No. 3 - 40.55% " " " " "
No. 4 - 39.05% " " " " "
No. 5 - 40.96% " " " " "
No. 6 - 39.20% " " " " "

Explaining any difference between the first results and the the second, the second set were "burned" at 750°C. for at least two hours longer than Group I, therefore the reaction did not go to completion in the first set. A minimum of 6 hours must now be recommended in the muffle furnace. While not conclusive, the results show no positive value for correctly delineating one zone of sedimentation from another by the amount of CO_2 and organic matter. The water content of the samples seems to be a good criterion but must be checked over the vertical extent of a quarry in order to determine its accuracy.

Quarry No. 1 was selected for study, due to its slight vertical extent and accessibility. It contains two different geologic formations and several horizons predominating in silicious replacement.

Samples were run in duplicate to check results. Some few did not check and were run again in duplicate until a check was assured. Results listed both in table form and graph form are submitted.

TABLE 3. PER CENT H_2O (HYGROSCOPIC) FOR QUARRY NO. 1

Level	Percentage H_2O	Mean
0a -	.0429)	.0426
0b -	.0423)	
1a -	.1432)	.1366
1b -	.1301)	
2a -	.0497)	.0492
2b -	.0487)	
3a -	.1325)	.1307
3b -	.1290)	
4a -	.0486)	.0489
4b -	.0493)	
5a -	.0755)	.0675
5b -	.0596)	
6a -	.0128)	.0162
6b -	.0196)	
7a -	.1695)	.1589
7b -	.1484)	
8a -	.0617)	.0601
8b -	.0585)	
9a -	.1441)	.1433
9b -	.1425)	
10a -	.1946)	.1933
10b -	.1920)	
11a -	.1115)	.1093
11b -	.1072)	
12a -	.1378)	.1324
12b -	.1270)	
13a -	.0096)	.0089
13b -	.0083)	
14a -	.0379)	.0382
14b -	.0386)	
15a -	missing	
15b -	"	
16a -	.0919)	.0903
16b -	.0887)	
17a -	.0505)	.0610
17b -	.0716)	
18a -	.0397)	.0436
18b -	.0475)	
19a -	.1998)	.1978
19b -	.1959)	
20a -	.1018)	.0979
20b -	.0941)	
21a -	.1127)	.1127
21b -	.1127)	
22a -	.0767)	.0756
22b -	.0745)	
23a -	.1859)	.1763
23b -	.1767)	
24a -	.0122)	.0130
24b -	.0139)	
25a -	.0386)	.0364
25b -	.0343)	
26a -	.0698)	.0659
26b -	.0621)	
27a -	.0469)	.0452
27b -	.0435)	
28a -	.0985)	.0912
28b -	.0839)	
29a -	.0839)	.0872
29b -	.0895)	
30a -	.0505)	.0584
30b -	.0663)	

TABLE 4. PER CENT ORGANIC CONTENT (CO_2) FOR QUARRY NO. 1

Level	Per Cent	Mean	Level	Per Cent	Mean
0a -	41.55	41.49	16a -	40.87	40.89
0b -	41.43		16b -	40.92	
1a -	41.85	41.83	17a -	42.05	42.02
1b -	41.81		17b -	42.00	
2a -	41.80	41.80	18a -	41.90	42.09
2b -	41.80		18b -	42.28	
3a -	-	41.55	19a -	38.51	38.57
3b -	-		19b -	38.63	
4a -	41.70	41.72	20a -	39.20	39.25
4b -	41.73		20b -	39.30	
5a -	40.89	40.89	21a -	40.14	40.16
5b -	40.89		21b -	40.18	
6a -	41.67	41.62	22a -	40.48	40.48
6b -	41.56		22b -	40.49	
7a -	41.21	41.19	23a -	41.18	41.14
7b -	41.16		23b -	41.11	
8a -	42.97	42.96	24a -	42.148	42.07
8b -	42.94		24b -	41.995	
9a -	40.91	40.80	25a -	41.7747	40.73
9b -	40.70		25b -	39.6972	
10a -	40.34	40.35	26a -	38.466	38.53
10b -	40.36		26b -	38.606	
11a -	40.72	40.75	27a -	45.3679	43.17
11b -	40.78		27b -	40.9774	
12a -	39.58	39.60	28a -	40.954	40.99
12b -	39.62		28b -	41.038	
13a -	42.73	42.71	29a -	37.962	38.02
13b -	42.70		29b -	38.088	
14a -	41.14	41.23	30a -	41.725	41.40
14b -	41.32		30b -	41.078	
15a -	41.79	41.84			
15b -	41.89				

Bulk Specific Gravity

Bulk specific gravity was reported incompletely in Progress Report No. 1 and will be reported completely here. The method used was:

$$\text{Bulk S. G.} = \frac{\text{wt. of sample in air}}{\text{loss of weight in water}} \quad \text{(no drying precautions)}$$

This was used to help evaluate the limestone and separate into zones differing in character. It is especially valuable in calculating the amount of pore space in a sample. A large enough sample was used in every case to make the error negligible when not observing drying precautions.

BULK SPECIFIC GRAVITY

QUARRY NO. 1, LEXINGTON, KY.

Level	Bulk Sp. G.
0	2.71
1	2.64
2	2.69
3	2.67
4	2.67
5	2.68
6	2.69
7	2.66
8	2.69
9	2.69
10	2.66
11	2.66
12	2.68
13	2.66
14	2.65
15	2.65
16	2.66
17	2.65
18	2.65
19	2.66
20	2.65
21	2.66
22	2.64
23	2.64
24	2.65
25	2.68
26	2.67
27	2.66
28	2.71
29	2.67
30	2.66
Quarry Average	2.666

BULK SPECIFIC GRAVITY

QUARRY NO. 2, MOUNT VERNON, KY.

Level	Bulk Sp. G.	Level	Bulk Sp. G.
1	2.69	51	2.67
2	2.69	52	2.67
3	2.69	53	2.68
4	2.70	54	2.67
5	2.70	55	2.72
6	2.70	56	2.70
7	2.70	57	2.72
8	2.70	58	2.51
9	2.70	59	2.69
10	2.70	60	2.67
11	2.62	61	2.67
12	2.52	62	2.62
13	2.43	63	2.68
14	2.43	64	2.66
15	2.43	65	2.58
16	2.54	66	2.59
17	2.69	67	2.59
18	2.68	68	2.58
19	2.68	69	2.58
20	2.69	70	2.57
21	2.69	71	2.58
22	2.69	72	2.59
23	2.65	73	Cover
24	2.63	74	2.45
25	2.61	75	2.42
26	2.61	76	2.36
27	2.62	77	2.49
28	2.68	78	2.56
29	2.70	79	2.31
30	2.68	80	2.61
31	2.68	81	2.62
32	2.70	82	2.67
33	2.71	83	2.66
34	Shale	84	2.64
35	2.69	85	2.65
36	2.70	86	2.67
37	2.69	87	2.66
38	2.70	88	2.55
39	2.72	89	2.61
40	2.70	90	2.65
41	2.65	91	2.64
42	2.65	92	2.70
43	2.65	93	2.65
44	2.66	94	2.63
45	2.70	95	2.67
46	2.66	96	2.64
47	2.66	97	2.67
48	2.66	98	2.64
49	2.70	99	2.66
50	2.66	100	2.69

BULK SPECIFIC GRAVITY

QUARRY NO. 2 (Continued)

Level	Bulk Sp. G.
101	2.69
102	2.69
103	2.69
104	2.65
105	2.53
106	2.56
107	2.62
108	2.56
109	2.63
110	2.69
111	Cover
112	2.68
113	2.55
114	2.55
115	2.68
116	2.57
117	2.61
118	2.64
119	2.69
120	2.65
121	2.65
122	2.48
123	2.57
124	2.62
125	2.69
126	2.69
127	2.69
128	2.66
129	2.69
130	2.68
131	2.65
132	Cover
133	2.62
134	2.69
135	2.66
Quarry Average	2.636

BULK SPECIFIC GRAVITY

QUARRY NO. 3, OLIVE HILL, KY.

Level	Bulk Sp. G.	Level	Bulk Sp. G.
1	2.68	34	2.30
2	2.69	35	2.30
3	2.68	36	2.40
4	2.68	37	2.57
5	2.67	38	2.56
6	2.69	39	2.62
7	2.67	40	2.55
8	2.67	41	2.56
9	2.65	42	2.62
10	2.68	43	2.59
11	2.67	44	2.60
12	2.67	45	2.61
13	2.68	46	2.63
14	2.68	47	2.56
15	2.69	48	2.59
16	2.67	49	2.51
17	2.66	50	2.51
18	2.67	51	2.69
19	2.64	52	2.54
20	2.64	53	2.68
21	Shale	54	2.53
22	2.65	55	2.66
23	2.65	56	2.64
24	2.67	57	2.63
25	2.67	58	2.56
26	2.67	59	2.57
27	2.60	60	2.63
28	2.61	61	2.48
29	2.58	62	2.52
30	2.50	63	2.63
31	2.44	64	2.64
32	2.66	65	2.64
33	2.57	Quarry Average - 2.606	

BULK SPECIFIC GRAVITY

QUARRY NO. 4, AVOCA, KY.

Level	Bulk Sp. G.
0	2.69
1	2.65
2	2.66
3	2.70
4	2.74
5	2.71
6	2.62
7	2.78
8	2.73
9	2.71
10	2.77
11	2.72
12	2.79
13	2.69
14	2.59
15	2.79
16	2.72
17	2.73
18	2.70
19	2.66
20	2.56
21	2.54
22	2.47
23	2.66
24	2.67
25	2.73
26	2.71
27	2.66
28	2.64
29	2.68
30	2.63
31	2.68
32	2.68
33	2.56
Quarry Average	2.677

Absolute Specific Gravity

A liberal definition of absolute specific gravity as applied to limestone may be described as the greatest possible concentration of matter per unit of volume. For example, a piece of stone as it is taken from the quarry is greatly expanded by a great number of minute void spaces. Its specific gravity in this state is referred to as its bulk specific gravity. If such stone could be compressed and compacted until all voids were eliminated, there would be a greater concentration of matter per unit of volume, and in the case of limestone there would be corresponding increase in the specific gravity. Having provided a basis for an absolute determination, the absolute values must be arrived at indirectly.

To measure the absolute specific gravity of a consolidated stone it is necessary to crush it and to break up the structures enclosing the voids. More simply, the stone is pulverized to pass a 100 mesh screen and the volume of a known mass of the material is measured by immersion.

In more detail, the procedure is described as follows: Representative samples of the various levels were pulverized using a desk type unit.

250 ml. calibrated and tared volumetric flasks were used as pyconometers. Approximately 200 - 250 grams of the samples were weighed into the flasks, the samples were covered with distilled water and attached to a vacuum outlet, 74 - 75 mm., agitated periodically until complete saturation was effected, usually from 2 to 3 hours, and then made up to volume with distilled water. The flask and contents were quickly weighed and the

temperature taken. An example of the method of calculating is shown below:

(Wt. of flask + sample) - wt. of flask = wt of sample

(Wt. of flask + sample + water) - (wt. of flask + sample) = wt. of water

Wt. of water + (wt. of water x .0010 correction for bouyancy of air) = actual wt. of water

Actual wt. of water/density of water at T°C = actual vol. of water

Vol. of flask - vol. of water = actual vol. of sample

Wt. of sample + (vol. of sample x .0010 correction for bouyancy of air) = actual wt. of sample

Actual wt. of sample/actual vol. of sample = Absolute specific gravity

All weighings were made on a balance having a capacity of over 1 kg. and a sensitivity of .001 gm. Precautions were taken to assure complete saturation, cleanliness of the flasks and accuracy in making up to volume.

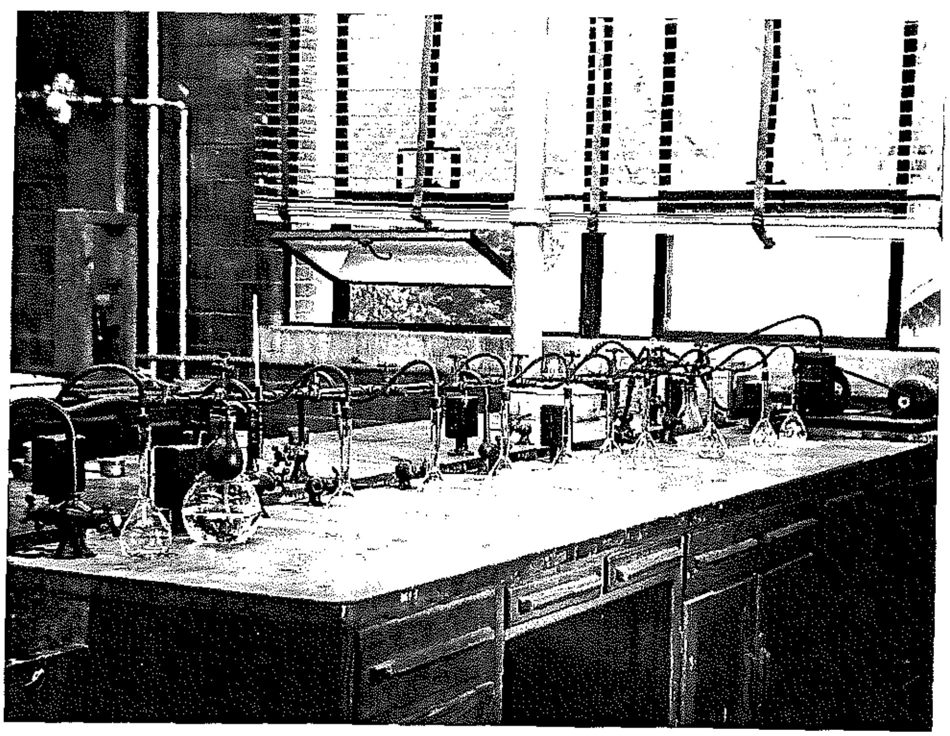


Fig. 3. Vacuum Line for Ten Simultaneous Evacuations

ABSOLUTE SPECIFIC GRAVITY

QUARRY NO. 1, LEXINGTON, KY.

Level	Abs. Sp. G.
0	2.7338
1	2.7138
2	2.7135
3	2.7249
4	2.7245
5	2.7297
6	2.7247
7	2.7241
8	2.7469
9	2.7320
10	2.7388
11	2.7238
12	2.7710
13	2.7454
14	2.7408
15	2.7278
16	2.7310
17	2.7262
18	2.7332
19	2.7379
20	2.7417
21	--
22	2.7503
23	2.7599
24	2.7480
25	2.7408
26	2.7387
27	2.7483
28	2.7292
29	2.7659
30	2.7069
Quarry Average -	2.7358

ABSOLUTE SPECIFIC GRAVITY

QUARRY NO. 2, MOUNT VERNON, KY.

Level	Abs. Sp. G.
1	2.7085
2	2.7071
3	2.7113
4	2.7109
5	2.7108
6	2.7060
7	2.7134
8	2.7160
9	2.7135
10	2.7085
11	2.7119
12	2.7019
13	2.7139
14	2.7110
15	2.7247
16	2.7119
17	2.7134
18	2.7139
19	2.7225
20	2.7170
21	2.7048
22	2.7043
23	2.7077
24	2.7079
25	2.7065
26	2.7065
27	2.7044
28	2.7093
29	2.7073
30	2.6973
31	2.7077
32	2.7090
33	2.7197
34	Shale
35	2.7128
36	2.7176
37	2.7343
38	2.7430
39	2.7234
40	2.7117
41	2.6967
42	2.7016
43	2.7015
44	2.7117
45	2.7262
46	2.7102
47	2.7049
48	2.7075
49	2.7137
50	2.7093
51	2.7083
52	2.7096
53	2.7049
54	--
55	2.7236
56	2.7346
57	2.7344
58	2.7120
59	2.7134
60	2.7148
61	2.7145
62	--
63	2.7204
64	2.7174
65	2.7127
66	2.7138
67	2.7677
68	2.7455
69	2.7595
70	2.7122
71	2.7365
72	2.7186
73	--
74	2.7068
75	2.7218
76	2.7107
77	2.7729
78	2.6952
79	2.7131
80	2.8083
81	2.7443
82	--
83	--
84	2.7145
85	2.7100
86	2.7134
87	--
88	2.7062
89	2.7102
90	2.7053
91	2.7076
92	2.7133
93	2.7118
94	2.6880
95	2.7022
96	--
97	2.6909
98	2.6961
99	2.7084
100	2.7089

QUARRY NO. 2 (Continued)

Level	Abs. Sp. G.
101	2.7047
102	2.7101
103	2.6925
104	2.7075
105	--
106	2.7170
107	2.7131
108	2.7108
109	2.7088
110	2.7319
111	2.7122
112	2.6973
113	2.7050
114	2.7125
115	2.7121
116	2.7187
117	2.7171
118	2.7171
119	2.7078
120	2.7115
121	2.7134
122	--
123	2.6629
124	2.6969
125	--
126	2.7013
127	2.7026
128	2.7104
129	2.7091
130	2.7282
131	2.7123
132	--
133	2.7046
134	2.7203
135	2.7097
Quarry Average -	2.7139

ABSOLUTE SPECIFIC GRAVITY

QUARRY NO. 3, OLIVE HILL, KY.

Level	Abs. Sp. G.
1	2.7042
2	2.6938
3	2.6978
4	2.7002
5	2.7098
6	2.6899
7	2.7005
8	2.7037
9	2.6961
10	2.6983
11	2.7070
12	2.7288
13	2.7504
14	2.7201
15	2.7302
16	2.7396
17	2.7679
18	2.6992
19	2.7113
20	2.7108
21	Shale
22	2.7811
23	2.7256
24	2.7984
25	2.8153
26	2.8148
27	2.7360
28	2.8350
29	2.8132
30	2.7924
31	2.6686
32	2.7236
33	2.7112
34	2.7374
35	2.7658
36	2.8050
37	2.7623
38	2.7179
39	2.7152
40	2.7484
41	2.7295
42	2.7119
43	2.7076
44	2.7105
45	2.7076
46	2.7097
47	2.7172
48	2.7180
49	2.7208
50	2.7198
51	2.7286
52	2.7322
53	2.7142
54	2.7117
55	2.7079
56	2.7097
57	2.7094
58	2.7204
59	2.7071
60	2.7241
61	--
62	2.7031
63	2.8018
64	2.7014
65	2.7028
Quarry Average	2.7294

ABSOLUTE SPECIFIC GRAVITY

QUARRY NO. 4, AVOCA, KY.

Level	Abs. Sp. G.
0	2.8816
1	2.8523
2	2.8493
3	2.8249
4	2.8432
5	2.8558
6	2.8527
7	2.8491
8	2.8362
9	2.8550
10	2.8542
11	2.9771
12	2.8599
13	2.8356
14	2.8461
15	2.8344
16	2.8413
17	2.8548
18	2.8421
19	2.8454
20	2.8510
21	--
22	2.8531
23	2.8470
24	2.8538
25	2.8316
26	2.8401
27	2.8313
28	2.8144
29	2.8295
30	2.8302
31	2.8395
32	2.8408
33	2.8421
Quarry Average -	2.8453

Porosity

From a quantitative standpoint, the porosity of limestone or other substance is the ratio of the volume of internal open spaces to the total volume of the specimen. The open spaces are variously referred to as "pores", "interstices", or "voids". The pores of a substance may be isolated from one another, or they may be intercommunicating, and it is in this latter sense that "available pore space", or "effective porosity" is spoken of in contradistinction to "total pore space" or "total porosity".

Porosity may be determined by direct or indirect method. The present method is an indirect method to be followed in the near future by a direct method. This portion of the report is concerned with "total porosity".

Total porosity by an indirect method is calculated from t previously determined physical properties, Bulk Specific Gravity and Absolute Specific Gravity. The Specific Gravity of a specimen is determined of the "bulk", including the limestone and its voids. This is the value referred to as the Bulk Specific Gravity. A large enough specimen was used in all cases to be able to ignore surface saturation phenomena as a negligible error.

The specimen was crushed to pass a 100 mesh screen and in the Absolute Specific Gravity determination all of the air was displaced by water, thus destroying all voids.

The difference in these two values represents the weight of material displaced by voids. This weight divided by the absolute specific gravity gives the volume of material displaced per unit volume and multiplying by 100 will place the figure as a percentage per unit volume or, for example:

Absolute Sp. Gr. - 2.8816
Bulk Sp. Gr. - 2.69
.1916 = wt. of material displaced by voids

.1916/2.8816 = volume of material displaced per unit vol. = .0665 ml.

.0665/1 ml. x 100 = 6.65% per unit volume

PERCENTAGE OF VOID SPACE PER UNIT VOLUME OF BULK MATERIAL

QUARRY NO. 1, LEXINGTON, KY.

Level	Per Cent Voids
0	.870%
1	2.719%
2	.866%
3	2.015%
4	2.000%
5	1.821%
6	1.273%
7	2.353%
8	2.071%
9	1.903%
10	2.877%
11	1.975%
12	3.284%
13	3.111%
14	3.313%
15	2.852%
16	2.600%
17	2.795%
18	3.044%
19	2.845%
20	3.345%
21	--
22	4.010%
23	4.334%
24	3.566%
25	2.218%
26	2.508%
27	3.213%
28	.703%
29	3.467%
30	1.733%
Quarry Average	2.523%

PERCENTAGE OF VOID SPACE PER UNIT VOLUME OF BULK MATERIAL

QUARRY NO. 2, MOUNT VERNON, KY.

Level	Per Cent Voids	Level	Per Cent Voids
1	0.683%	51	1.414%
2	0.632%	52	1.461%
3	0.786%	53	.920%
4	0.402%	54	--
5	0.398%	55	.315%
6	0.222%	56	1.265%
7	0.494%	57	.527%
8	0.589%	58	7.448%
9	0.497%	59	.862%
10	0.589%	60	1.650%
11	3.446%	61	1.693%
12	6.960%	62	--
13	10.395%	63	1.485%
14	10.365%	64	2.112%
15	10.449%	65	4.892%
16	6.339%	66	4.562%
17	0.862%	67	6.420%
18	1.249%	68	6.028%
19	1.561%	69	6.505%
20	0.994%	70	5.243%
21	0.547%	71	5.719%
22	0.529%	72	4.730%
23	2.131%	73	--
24	2.877%	74	9.487%
25	3.565%	75	11.088%
26	3.565%	76	12.938%
27	3.121%	77	10.202%
28	1.081%	78	5.016%
29	0.270%	79	14.857%
30	0.641%	80	7.061%
31	1.023%	81	4.529%
32	0.332%	82	--
33	0.357%	83	--
34	Shale	84	2.744%
35	0.840%	85	2.214%
36	0.648%	86	1.599%
37	1.620%	87	--
38	1.568%	88	5.772%
39	0.125%	89	3.697%
40	0.431%	90	2.044%
41	1.732%	91	2.497%
42	1.910%	92	.490%
43	1.906%	93	2.279%
44	1.906%	94	2.158%
45	0.961%	95	1.192%
46	1.852%	96	--
47	1.660%	97	.777%
48	1.754%	98	2.081%
49	0.505%	99	1.787%
50	1.820%	100	.698%

QUARRY NO. 2 (Continued)

Level	Per Cent Voids
101	.543%
102	.742%
103	.093%
104	2.124%
105	--
106	5.778%
107	3.431%
108	5.552%
109	2.909%
110	1.534%
111	--
112	.642%
113	5.730%
114	5.991%
115	1.183%
116	5.469%
117	3.942%
118	2.837%
119	.657%
120	2.268%
121	2.336%
122	--
123	3.488%
124	2.851%
125	--
126	.418%
127	.466%
128	1.859%
129	.705%
130	1.767%
131	2.297%
132	--
133	3.128%
134	1.114%
135	1.834%
Quarry Average	2.864%

PERCENTAGE OF VOID SPACE PER UNIT VOLUME OF BULK MATERIAL

QUARRY NO. 3, OLIVE HILL, KY.

Level	Per Cent Voids	Level	Per Cent Voids
1	.845%	34	15.979%
2	.141%	35	16.841%
3	.660%	36	14.438%
4	.748%	37	6.961%
5	1.469%	38	5.810%
6	.000%	39	3.506%
7	1.129%	40	7.219%
8	1.246%	41	6.210%
9	1.710%	42	3.389%
10	.678%	43	4.343%
11	1.367%	44	7.766%
12	2.155%	45	3.605%
13	2.560%	46	2.941%
14	1.474%	47	5.785%
15	1.472%	48	4.709%
16	2.540%	49	7.748%
17	3.898%	50	7.714%
18	1.082%	51	1.415%
19	2.630%	52	7.035%
20	2.612%	53	1.260%
21	shale	54	6.700%
22	4.714%	55	1.769%
23	2.774%	56	2.572%
24	4.588%	57	2.930%
25	5.161%	58	5.896%
26	5.144%	59	5.064%
27	4.971%	60	3.454%
28	7.936%	61	--
29	8.249%	62	6.774%
30	10.471%	63	6.132%
31	8.566%	64	2.265%
32	2.335%	65	2.323%
33	5.208%	Quarry Average	4.462%

PERCENTAGE OF VOID SPACE PER UNIT VOLUME OF BULK MATERIAL

QUARRY NO. 4, AVOCA, KY.

Level	Per Cent Voids
0	6.65%
1	7.10%
2	6.66%
3	4.42%
4	3.63%
5	5.11%
6	8.16%
7	2.43%
8	3.74%
9	5.08%
10	2.95%
11	8.64%
12	2.44%
13	5.13%
14	9.00%
15	1.57%
16	4.27%
17	4.37%
18	5.00%
19	6.52%
20	10.21%
21	--
22	13.43%
23	6.57%
24	6.44%
25	3.59%
26	4.58%
27	6.05%
28	6.20%
29	5.28%
30	7.07%
31	5.62%
32	5.66%
33	9.93%
Quarry Average	5.864%

Chemical Analysis

The analysis of Quarry No. 1 was reported in more detail (Appendix 2 of the previous report) than the later results. The later analyses do not involve the analysis of the insoluble residues. They are reported as the percentage of insoluble material present, and the composition of the residue is considered to be largely SiO_2, in the form of Quartz and other silicates. This difference does not detract greatly from the significance of the results, if the per cent of insoluble residue is treated as being indicative of the per cent of SiO_2.

The results for Quarry No. 1 and Quarry No. 4 are submitted here complete. Quarry No. 2 is reported partially complete. In addition to the incomplete data for Quarry No. 2, it is of interest to compare these results with an average for the quarry which was computed from data taken from the Annual Report of Quarries, prepared by the Testing Laboratory, January, 1947. These averages are listed below and properly labeled.

As a matter of further interest, four levels for Quarry No. 3 were listed in the Annual Report of Quarries. These values indicate approximate averages of 65% $CaCO_3$, 20% $MgCO_3$, 14% insoluble residue, and 1% R_2O_3. Actual quarry average for insoluble residue is 11.9%. These approximations are mentioned merely to indicate the trend of the quarry.

Analysis of Quarry No. 1

Level	Zone	$CaCO_3$	$MgCO_3$	Fe_2O_3	SiO_2	Al_2O_3	$Ca_3(PO_4)_2$
0- 5	1	86.10%	6.94%	.75%	3.51%	1.76%	.93%
6-11	2	82.60%	8.51%	.84%	3.78%	1.69%	2.55%
12-18	3	85.80%	7.28%	.61%	2.15%	1.46%	2.61%
19-24	4	82.00%	8.00%	.83%	3.95%	2.32%	2.81%
25-30	5	87.40%	5.29%	.53%	2.26%	1.53%	2.93%
Averages -		84.78%	7.20%	.71%	3.13%	1.75%	2.37%

Analysis of Quarry No. 2

Level	Zone	$CaCO_3$	$MgCO_3$	R_2O_3	Insol. Res.
.	.	.	.	.	.
2- 6	2	96.16%	trace	1.21%	4.70%
7- 9	3	97.10%	"	1.02%	2.59%
10-16	4	98.22%	"	.71%	1.34%
17-22	5	94.10%	"	1.23%	4.56%
23-29	6	94.30	"	1.55%	3.98%
.	.	.	.	.	.
.	.	.	.	.	.
55-60	11	96.17%	3.24%	.71%	1.67%
61-63	12	93.71%	5.82%	.85%	1.98%
64-78	13	91.19%	4.59%	.79%	2.95%
79-82	14	73.72%	18.01%	3.47%	3.98%
83-86	15	94.15%	4.49%	.79%	3.15%
.	.	.	.	.	.
Averages for quarry as indicated by Annual Report of Quarries:		94.12%	1.68%	.51%	3.18%

Analysis of Quarry No. 4

Level	Zone	$CaCO_3$	$MgCO_3$	R_2O_3	Insol. Res.
0- 3	1	55.89%	35.40%	2.76%	5.96%
4- 9	2	59.10%	36.70%	1.90%	3.72%
10-11	3	61.37%	35.09%	2.22%	1.36%
12-18	4	59.57%	37.24%	1.78%	2.39%
19-23	5	57.37%	39.37%	.96%	3.96%
24-28	6	69.99%	23.01%	1.14%	6.34%
29-33	7	68.82%	23.78%	1.12%	6.19%
Averages -		61.73%	32.94%	1.70%	4.27%

Thin Sections

Thin sections have been completed for all the quarries and a complete file of photomicrographs is on hand. The structure is nowhere exclusive as an identical structure may be found in an accepted and a rejected quarry.

Quarry No. 4, the source rated as excellent, has so nearly a homogenous structure as to be phenomenal. Differences occur only in size of crystals and the impurities present, although to the observer, no measurable difference may be seen in the impurities. A photomicrograph is submitted for illustration:

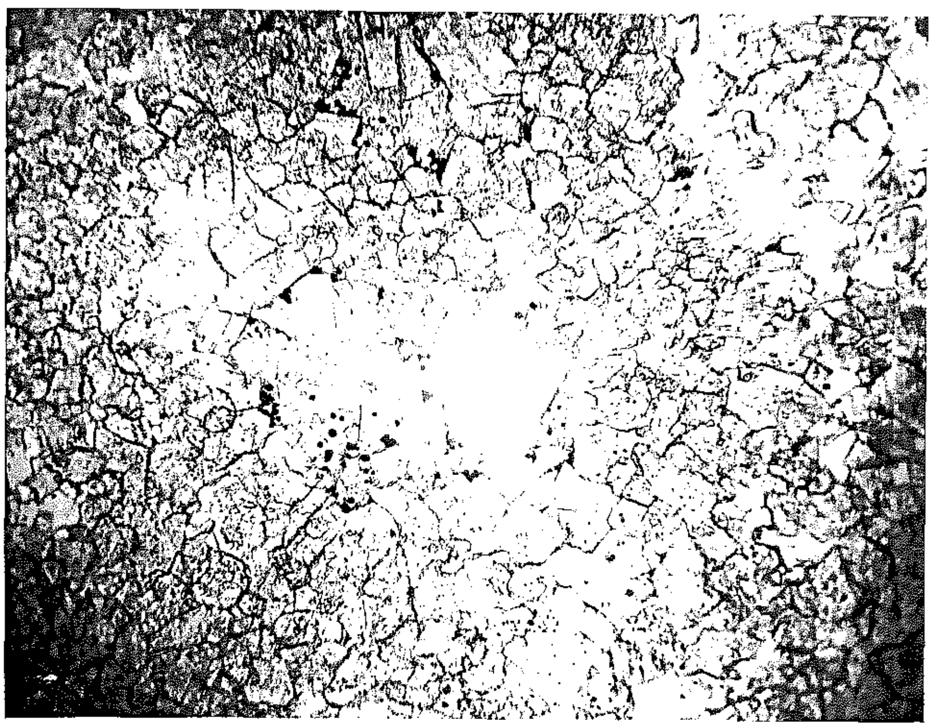


Fig. 4. Photomicrograph of Thin Section, Quarry No. 4

Until such time as the tests on individual zones show their relative durability, no special inference can be placed on structure.

CONCLUSIONS

Data presented in the foregoing section was subject to the usual experimental error and is used as such. It is the intent of the authors to discuss as specifically as possible with this information, the results and their significance in this problem.

The overwhelming fact this information presents is that due to the wide range in physical properties, it is fallacious to analyze a quarry as a whole. The act of breaking up a quarry into zones of sedimentation does not make these physical properties specific, so that generalities must always be used. The smaller divisions make these properties more nearly specific so that it is more useful.

In this discussion, there appears a set of graphs with figures presented for standard deviation, coefficient of variation, maximum deviation, and the usual quarry average. Standard deviation is calculated from the formula, sigma =

$$\sqrt{\frac{x_1^2 + x_2^2 + \ldots\ x_n^2}{n} - \bar{x}^2}$$

where n = number of observations and $\bar{x}$ = average figure. Coefficient of variation is calculated from the formula, $V = 100x\ \frac{\text{sigma}}{\bar{x}}$ which is expressed as a percentage. Maximum deviation indicates the range over which the values occur. Quarry average is merely the arithmetic mean.

Insoluble Residue is the most valuable criteria to date:

(Fair)	Quarry No. 1 -	5.145%
(Good)	Quarry No. 2 -	3.880%
(Poor)	Quarry No. 3 -	11.900%
(Excellent)	Quarry No. 4 -	4.166%

Quarries Nos. 2 and 4 are the lowest in insoluble residue and the best in performance. They do not fall exactly in line with our ratings, however the difference is slight. The only other obvious property which could serve to differentiate these is one of hardness or tenacity. This could involve a formula of multiplying the insoluble residue by the reciprocal of the hardness or breaking strength. Subsequent tests should show whether this is true or not.

Determinations of hygroscopic water and total organic content have been abandoned as being untenable. Not enough difference is shown over the vertical extent of a quarry to use this evaluation, particularly since a chemical analysis is available.

The percent porosity (absolute) has indicated nothing other than the fact that not much difference occurs in any of the quarries. Effective porosity should be the next test and in comparison to permeability may be a valuable test.

Permeability is interesting in that the horizontal direction generally shows more permeability than the vertical. This would possibly indicate that limestone has slight differences in strength with regard to orientation. No comparable differences may be noted over the total quarries. As mentioned earlier, a study of pore size and shape will be run and this should determine which fall into the capillary limits. In conjunction with permeability, this could be very pertinent.

Absolute Specific Gravity - It is only by correlation of the various properties of limestone that we are able to visualize the "over-all" picture of how these properties are related, and to understand how the limestone itself is put together. Absolute specific gravity is, as indicated, an absolute value and provides a firm basis upon which to base correlations. Absolute specific gravity has already been defined as being the greatest possible concentration of matter per unit of volume. In other words, it is the maximum density which could be obtained by "close packing" of the particles which make up the limestone. Under such ideal conditions, all voids are eliminated and the specific gravity measured is necessarily unit weight divided by the sum of the volumes of the components as determined from their specific gravity constants and percentage present.

For illustration, these relations are shown below:

Component	Percent Present	Wt. per gram		Sp.Gr. Constant		Vol. per gram
SiO_2	3.13%	.0313	÷	2.30	=	.01361
Fe_2O_3	.71%	.0071	÷	5.25	=	.00135
Al_2O_3	1.75%	.0175	÷	3.7	=	.00473
$Ca_3(PO_4)_2$	2.37%	.0237	÷	3.14	=	.00755
$CaCO_3$	84.78%	.8478	÷	2.711	=	.31550
$MgCO_3$	7.20%	.0720	÷	3.037	=	.02371
	Total Volume per gram				=	.36645

1 gram ÷ .36645 = 2.730
Actual Quarry Average = 2.7358

It is easy to see that if the composition is known, the absolute specific gravity can be calculated with fair accuracy. In addition, the absolute specific gravity itself is very indicative of the composition.

Bulk Specific Gravity - is related to the absolute value by virtue of the loose natural arrangement of the limestone as contrasted to the ideal arrangement, which eliminates the void spaces. The two differ only to the amount of void spaces.

It has been shown already that the two determinations are used to calculate the percentage of void space per unit volume of bulk material. This value leads up to questions as to how much of this value is effective and vulnerable to saturation with water, and how much of this void space is isolated or, in effect, provides "air cushions" for the expansions and contractions due to freezing and thawing. These questions provide incentive for future work. The possibility of establishing limits or a limiting ratio between the two values is worthy of further consideration.

Chemical Analysis. Chemical analyses add to the picture by establishing the percentages of materials or minerals which compose the rock. Limestone is, first, a carbonate rock. Other materials are superfluous and probably interfered with crystallization and caused imperfect cleavage in the three planes. These generalities add emphasis to the insoluble residue criteria for discriminating between limestones. High percentages of insoluble materials disrupt the homogeneity of the stone. Carbonates, $CaCO_3$ and $MgCO_3$, are considered stable and occur with uniform crystallization and cleavage. Proof of this idea is seen in the performance record of Quarry No. 4.

There follow a tabulation of data which is intended to illustrate the absence of homogeneity between the various levels of the quarries as determined by their physical properties.

Standard Deviation

	Fair Quarry No. 1	Good Quarry No. 2	Poor Quarry No. 3	Excellent Quarry No. 4
Insol. Res.	2.588	3.039	8.63	2.542
Abs. Sp. G.	.0706	.063	.496	.143
% Voids	.893	2.874	3.424	2.447
Bulk Sp. G.	.0316	.0895	.1413	.105
Permeability	.117	21.717	.340	5.68

Coefficient of Variation

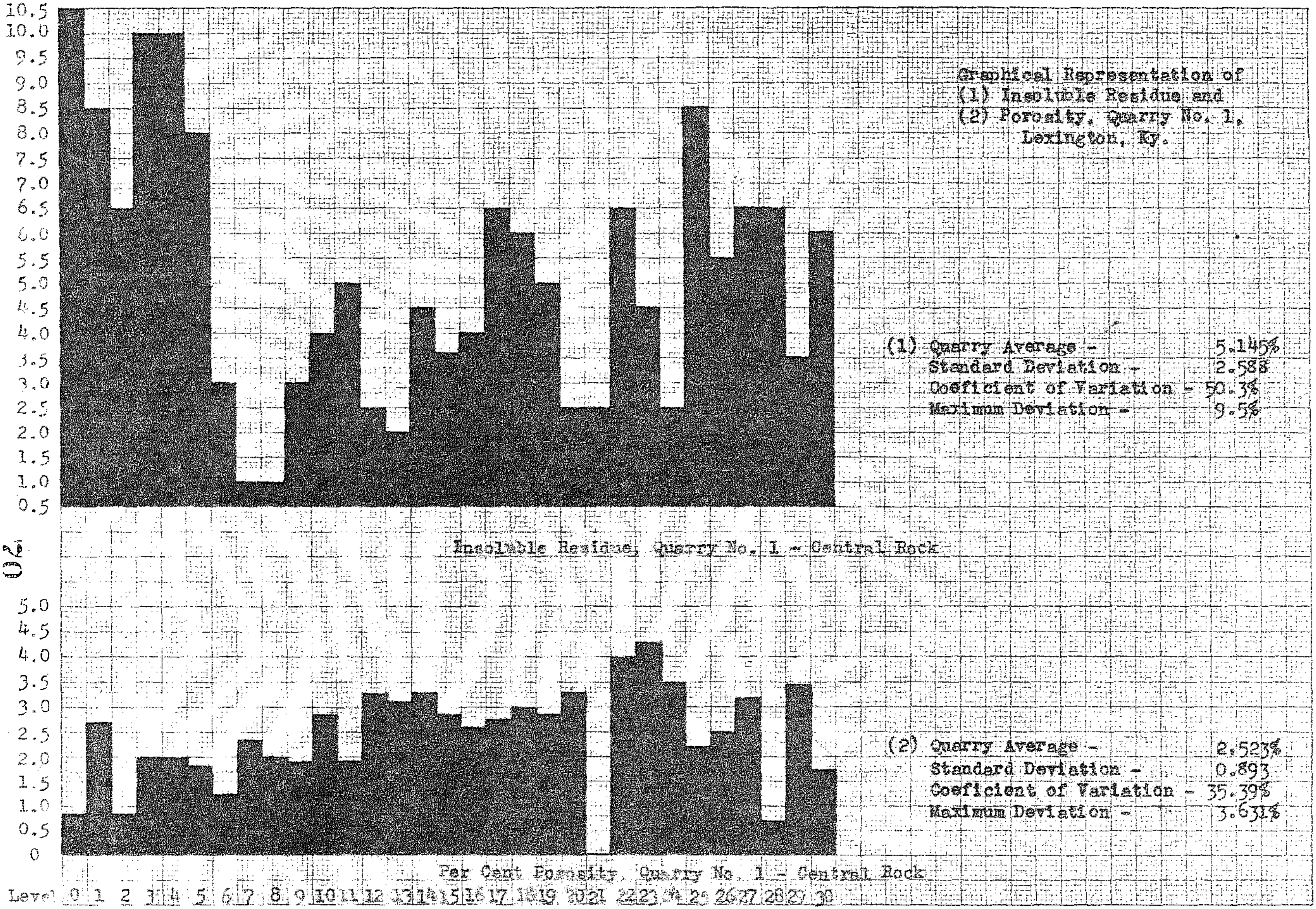
	Fair Quarry No. 1	Good Quarry No. 2	Poor Quarry No. 3	Excellent Quarry No. 4
Insol. Res.	50.3%	78.3%	72.5%	61.02%
Abs. Sp. G.	2.58%	2.32%	18.17%	5.03%
% Voids	35.39%	100.3%	76.92%	41.73%
Bulk Sp. G.	1.19%	3.39%	5.42%	3.92%
Permeability	68.1%	616.6%	237.6%	302.8%

Range - (Maximum - Minimum)

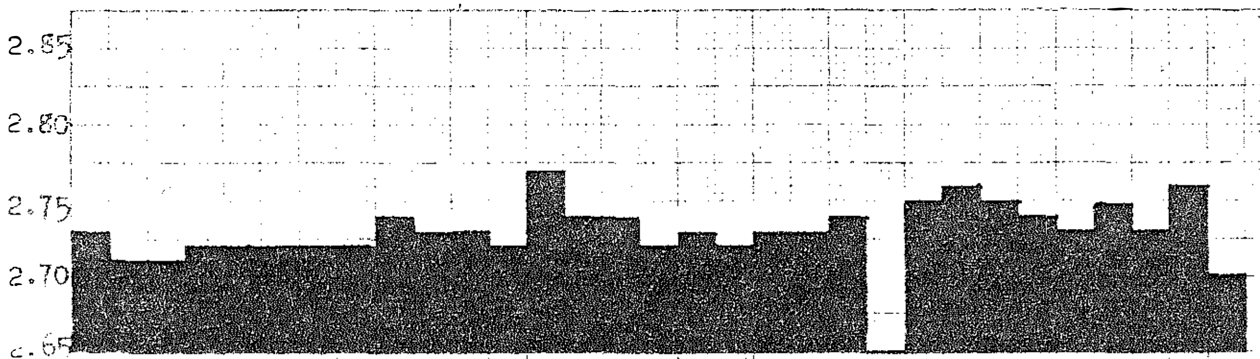
	Fair Quarry No. 1	Good Quarry No. 2	Poor Quarry No. 3	Excellent Quarry No. 4
Insol. Res.	9.5	17.0	58.0	9.25
Abs. Sp. G.	.641	.110	.166	.1627
% Voids	3.631	14.732	16.841	11.86
Bulk Sp. G.	.07	.41	.39	.32
Permeability	1.509	240.922	1.741	29.890

Quarry Averages

	Fair Quarry No. 1	Good Quarry No. 2	Poor Quarry No. 3	Excellent Quarry No. 4
Insol. Res.	5.145	3.88	11.90	4.166
Abs. Sp. G.	2.7358	2.7139	2.7294	2.8453
% Voids	2.523	2.864	4.462	5.864
Bulk Sp. G.	2.666	2.642	2.606	2.677
Permeability	.1719	3.522	.1431	1.876


Graphical Representation of
(1) Insoluble Residue and
(2) Porosity, Quarry No. 1,
Lexington, Ky.
(1) Quarry Average - 5.145%
Standard Deviation - 2.588
Coeficient of Variation - 50.3%
Maximum Deviation - 9.5%
Insoluble Residue, Quarry No. 1 - Central Rock
(2) Quarry Average - 2.523%
Standard Deviation - 0.893
Coeficient of Variation - 35.39%
Maximum Deviation - 3.631%
Per Cent Porosity, Quarry No. 1 - Central Rock
Level

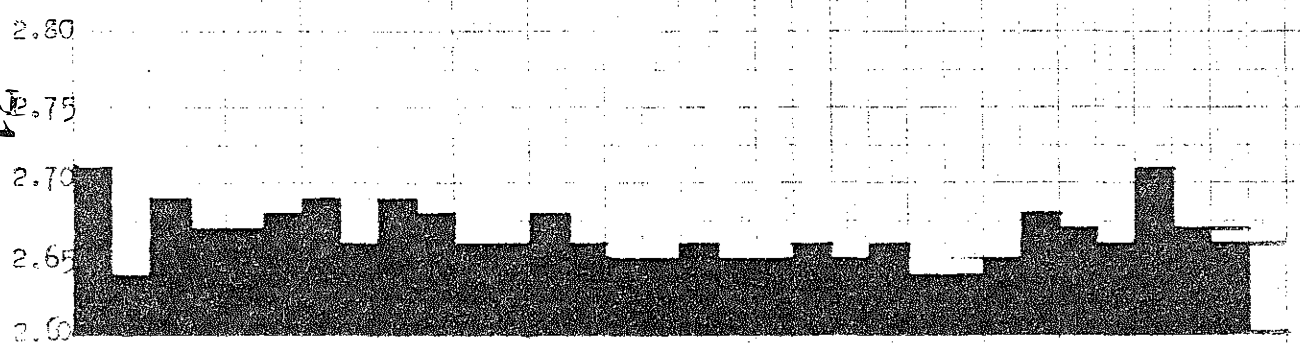
Graphical Representation of
(1) Absolute Specific Gravity,
(2) Bulk Specific Gravity, and
(3) Permeability of Quarry No. 1,
Lexington, Ky.



(1)

Quarry Average -		2.7358
Standard Deviation -		0.0706
Coefficient of Variation -		2.58%
Maximum Deviation -		0.0641

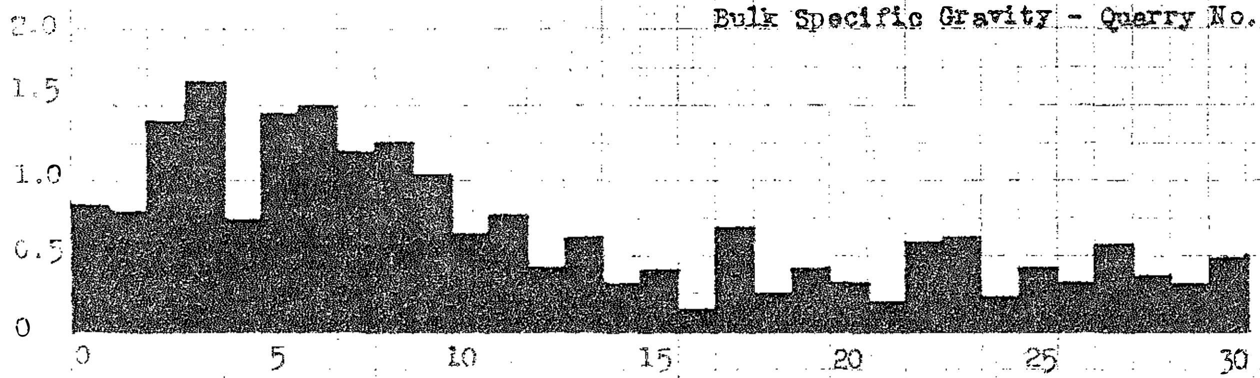
Absolute Specific Gravity - Quarry No. 1



(2)

Quarry Average -		2.665
Standard Deviation -		.0316
Coefficient of Variation -		1.19%
Maximum Deviation -		.07

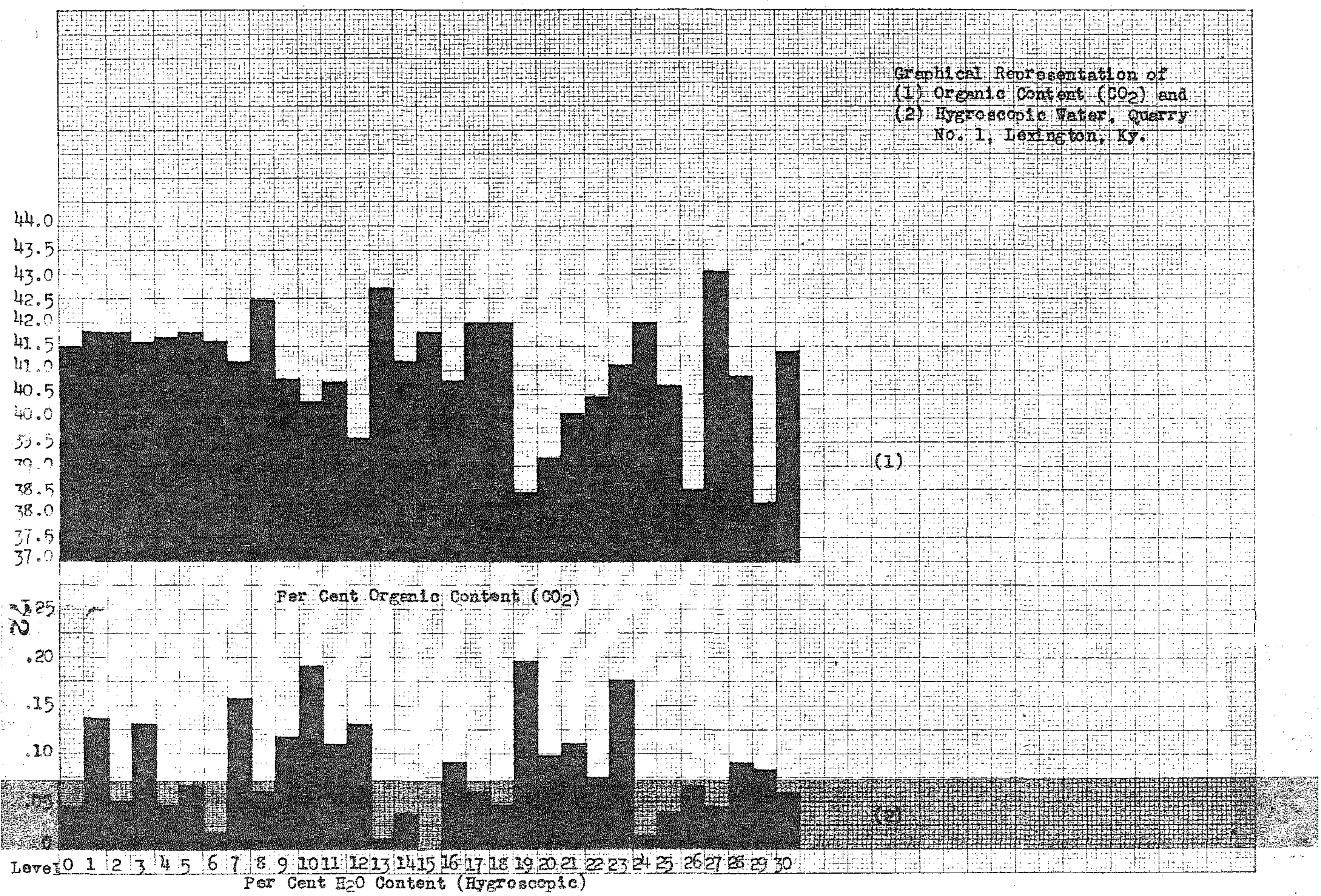
Bulk Specific Gravity - Quarry No. 1

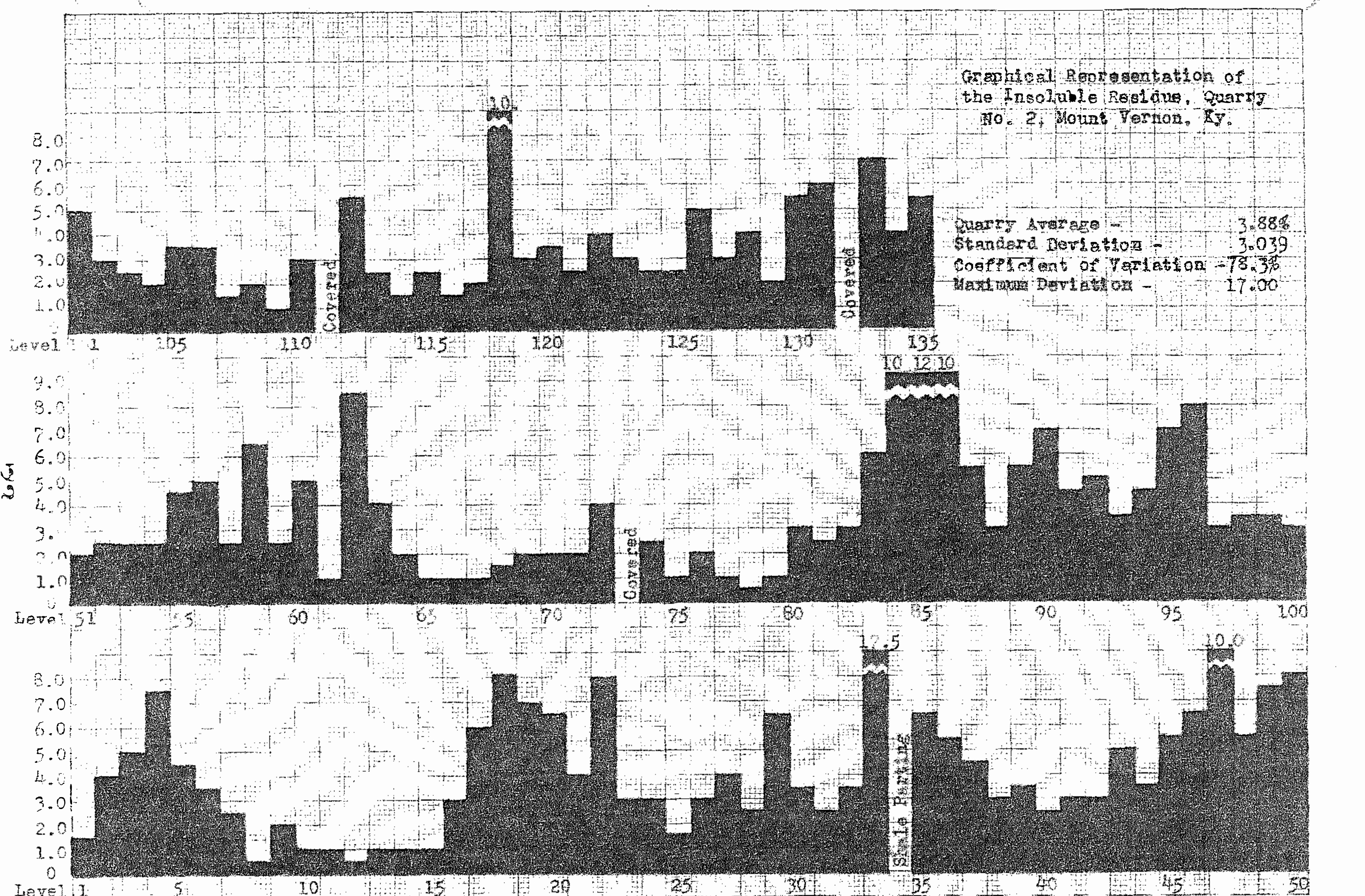


(3)

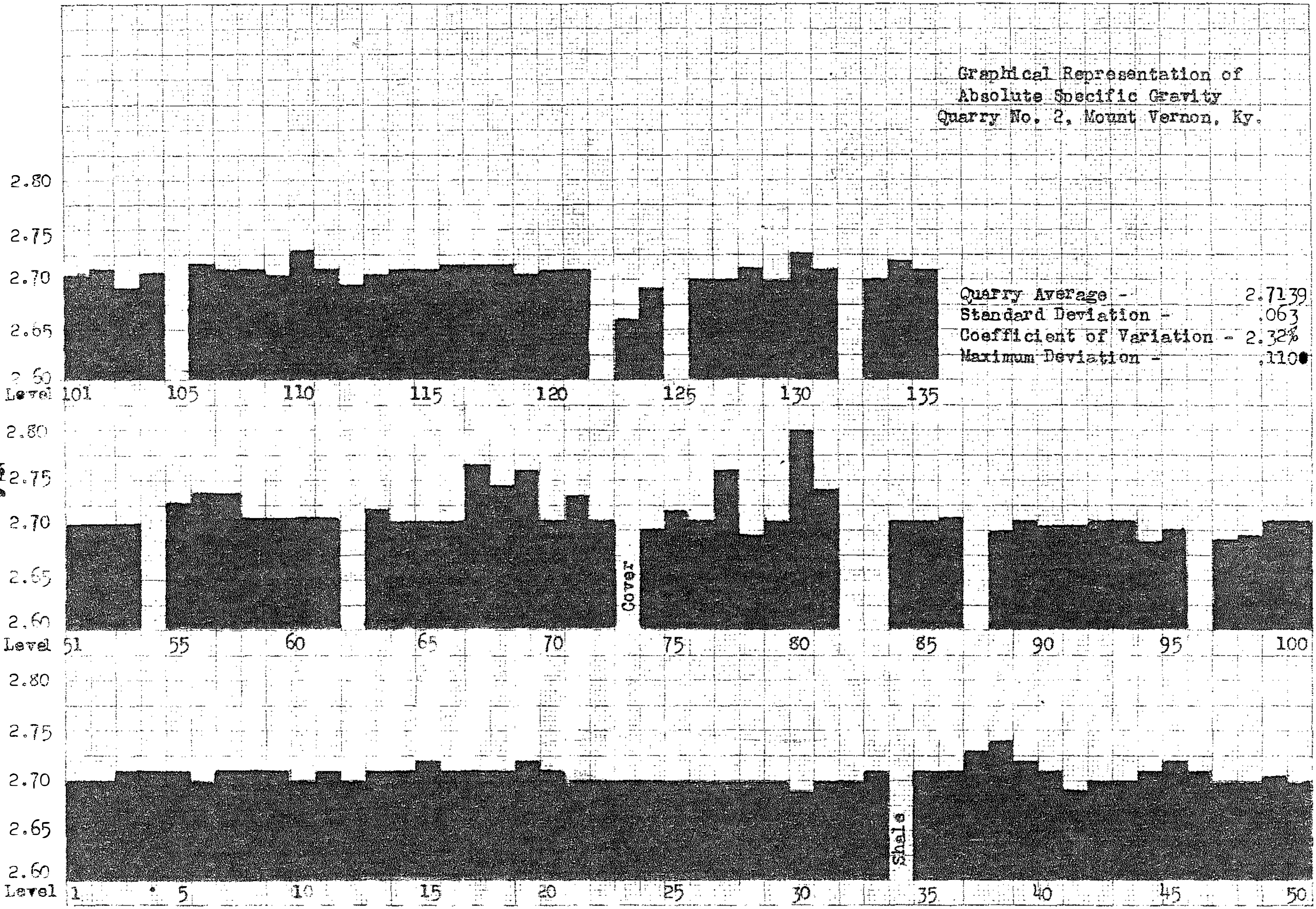
Quarry Average -		.1719
Standard Deviation -		.117
Coefficient of Variation -		68.1%
Maximum Deviation -		1.509%

Averaged Permeability - Quarry No. 1

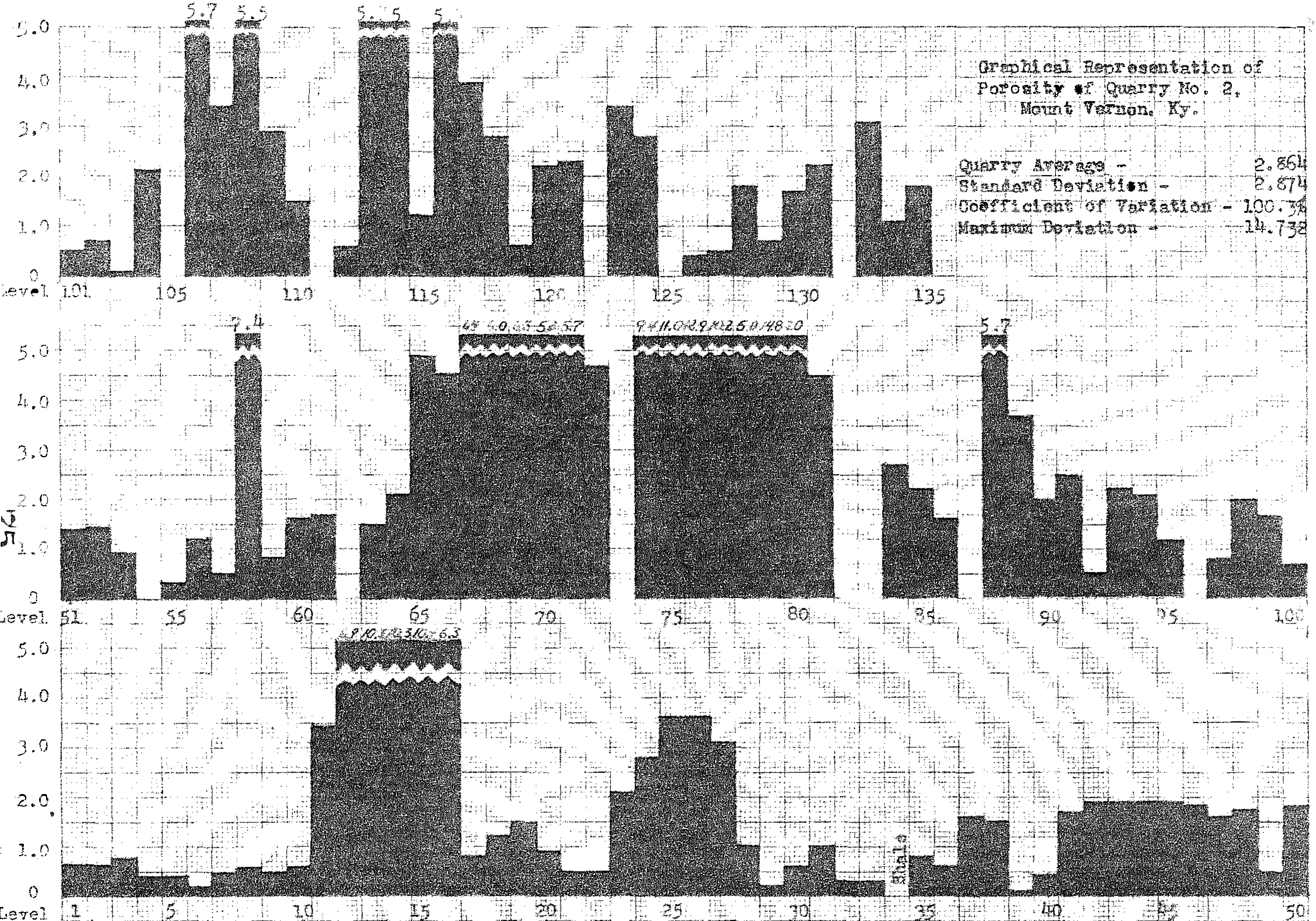

Graphical Representation of
(1) Organic Content (CO_2) and
(2) Hygroscopic Water, Quarry
No. 1, Lexington, Ky.
(1)
(2)
Per Cent Organic Content (CO_2)
Per Cent H_2O Content (Hygroscopic)
Level
44.0
43.5
43.0
42.5
42.0
41.5
40.5
40.0
38.5
38.0
37.5
37.0
.20
.15
.10
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30



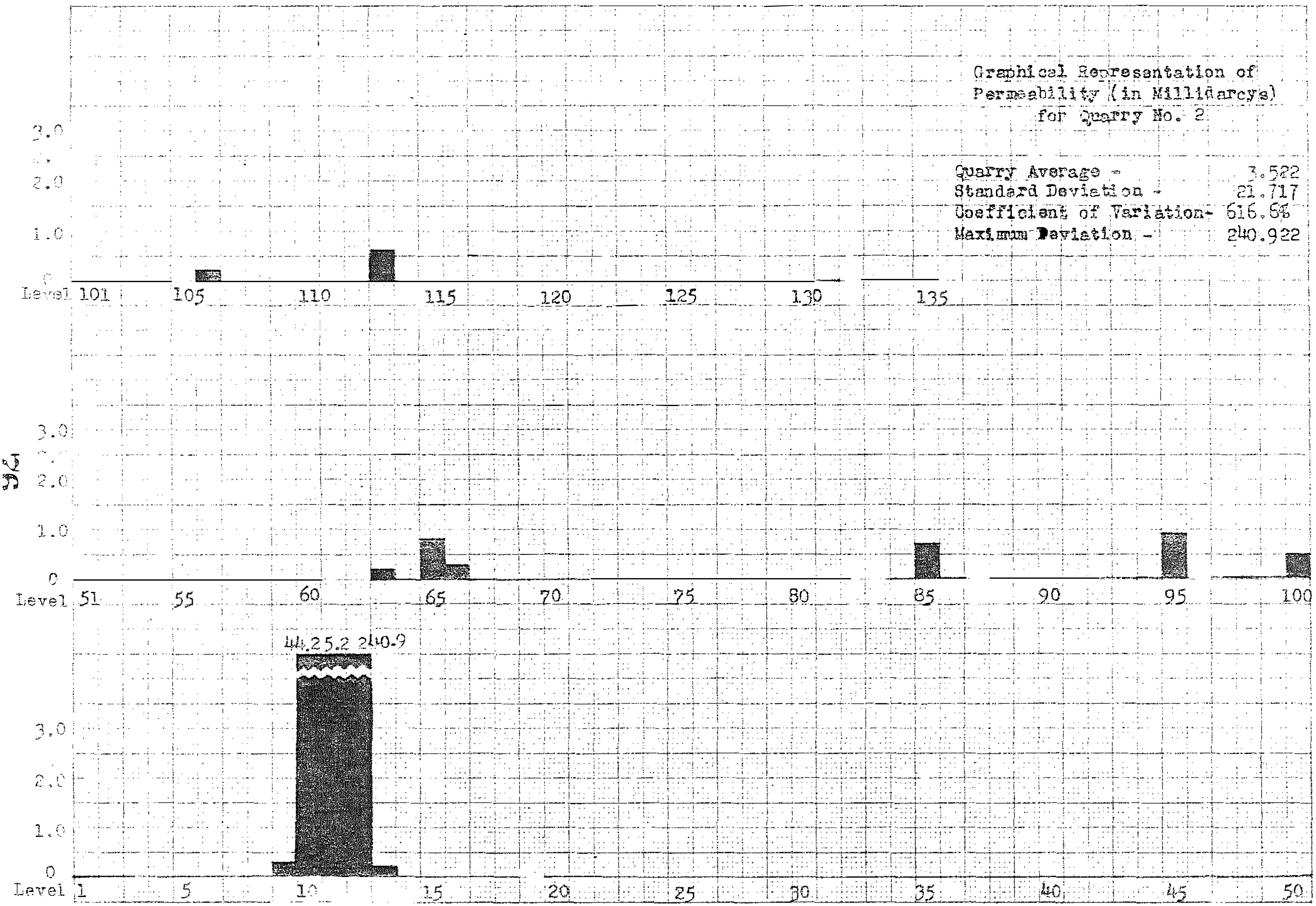
Insoluble Residue - Quarry No. 2



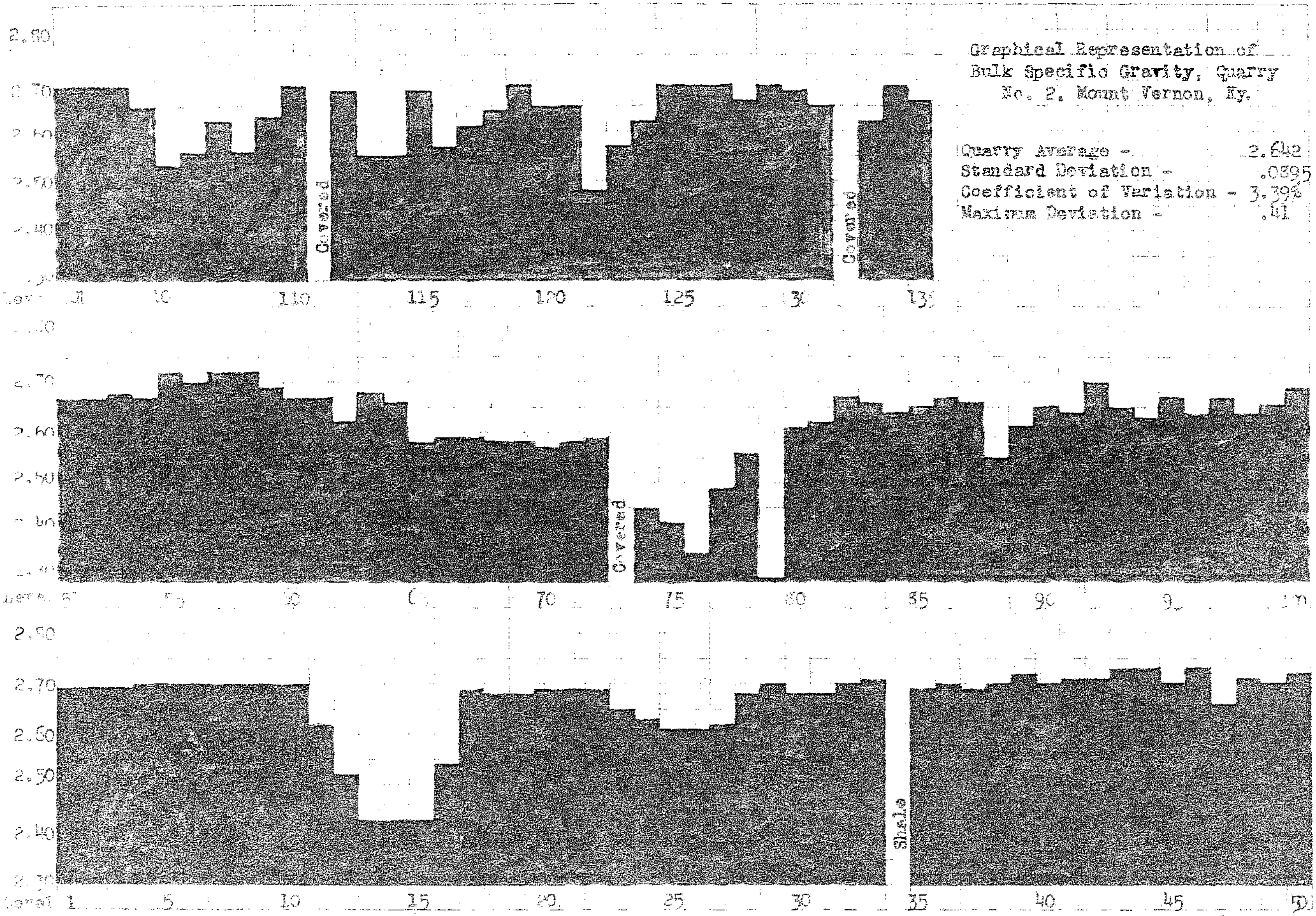
Absolute Specific Gravity - Quarry No. 2



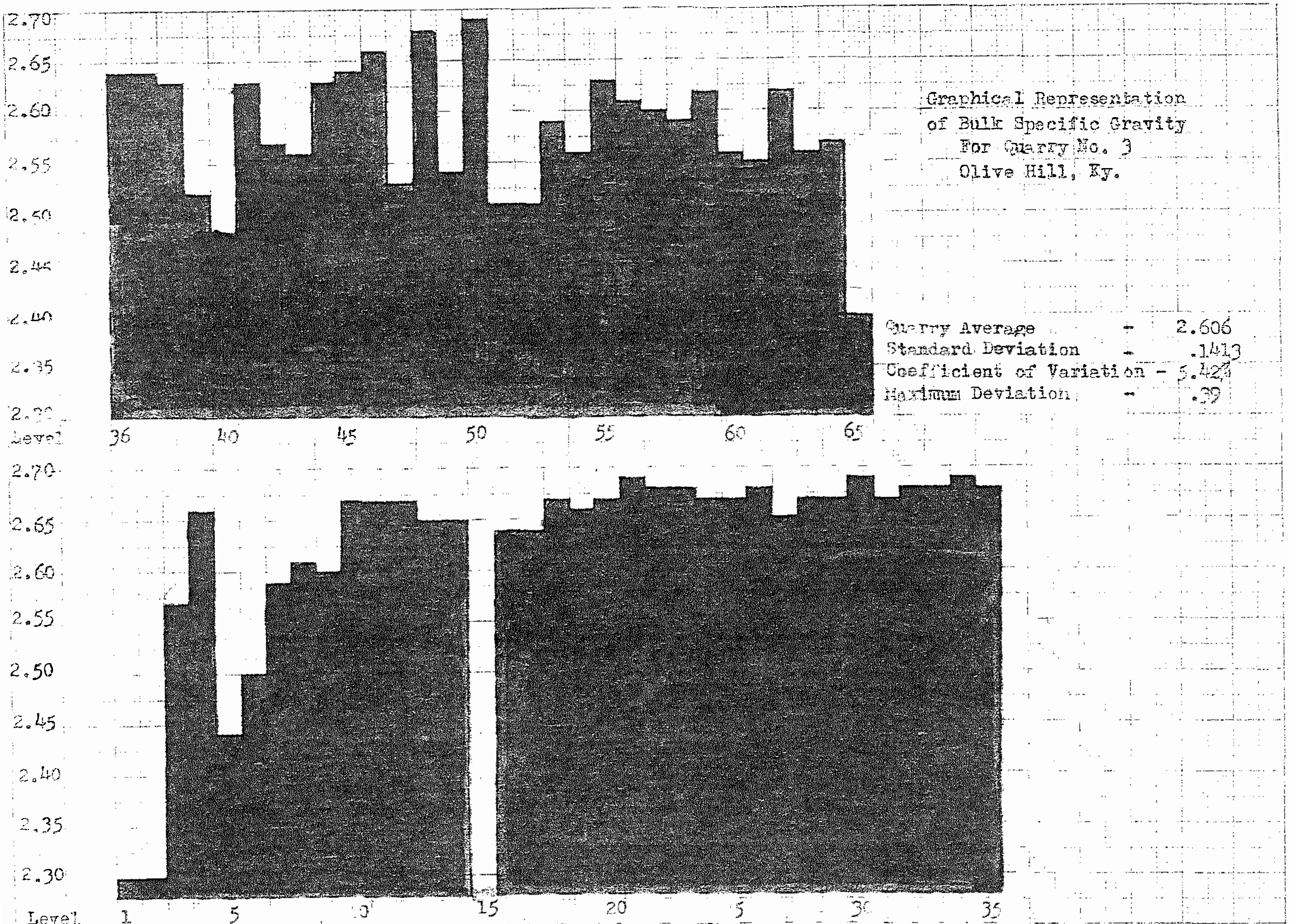
Porosity - Quarry No. 2



Permeability (in Millidarcys) - Quarry No. 2



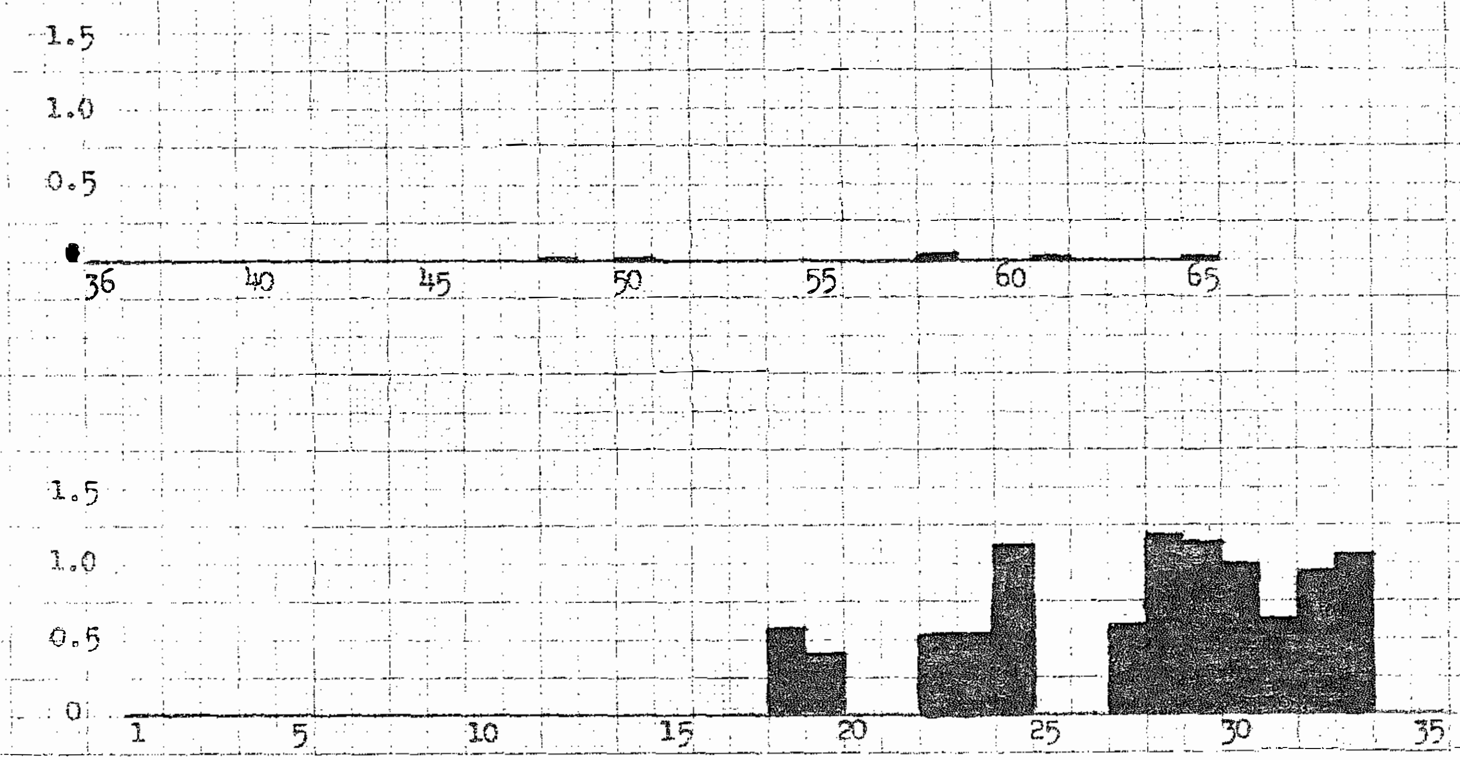
Bulk Specific Gravity - Quarry No. 2



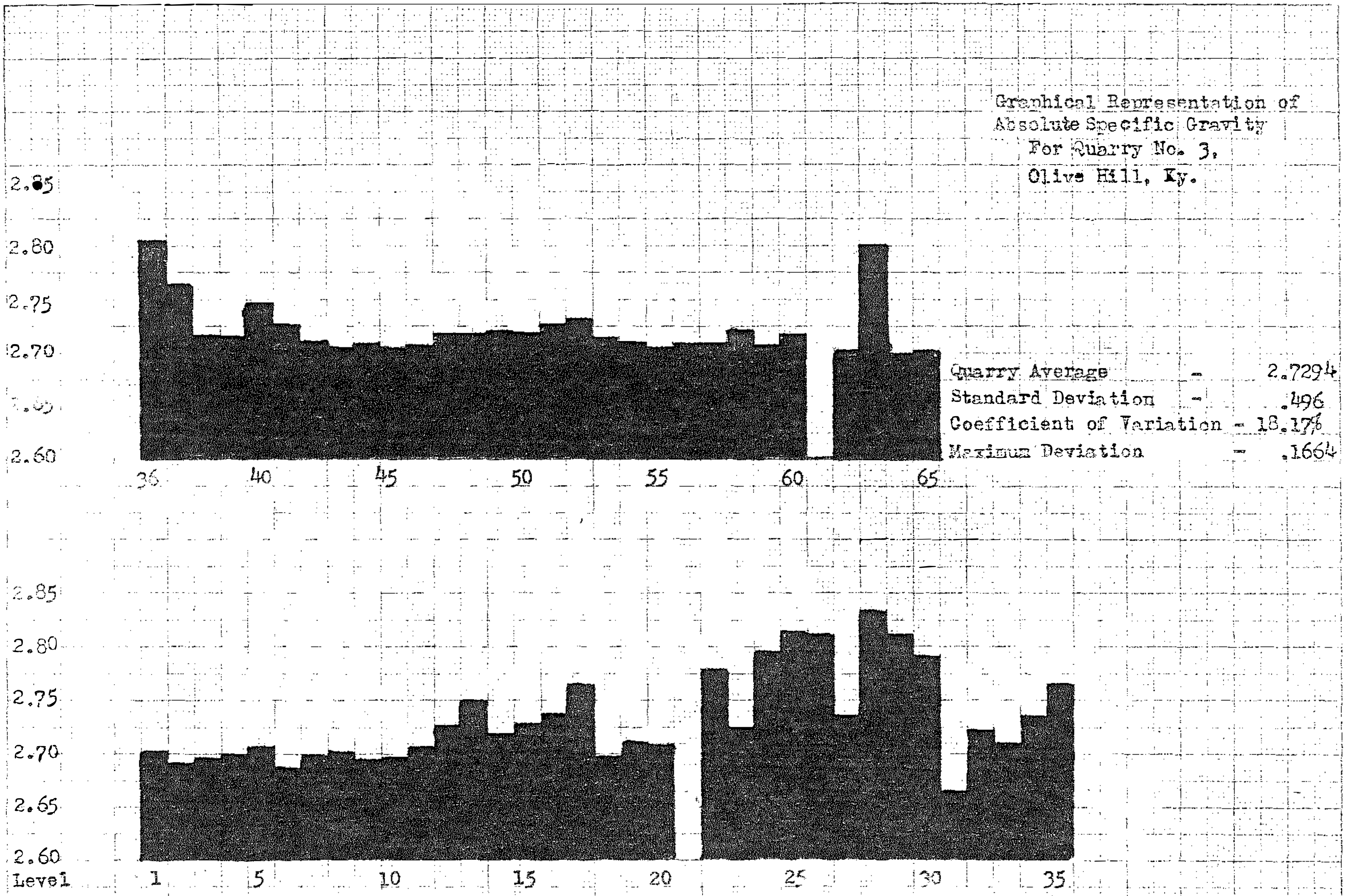
ul' S ecific ra it , ua y 7

Graphical Representation of
Permeability (in Millidarcys).
Quarry No. 3, Olive Hill, Ky.

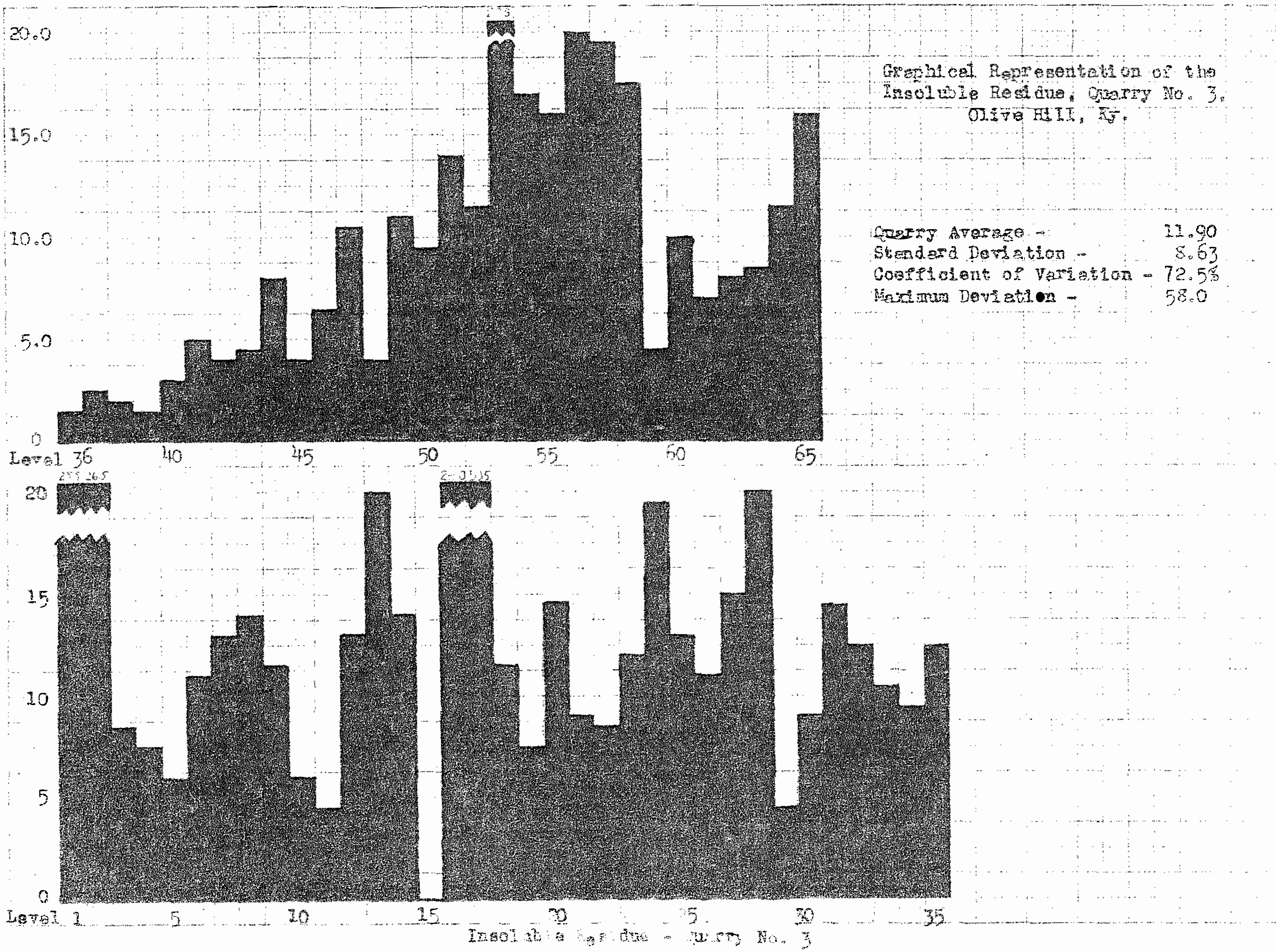
Quarry Average - .1431
Standard Deviation - .340
Coefficient of Variation- 237.6%
Maximum Deviation - 1.741

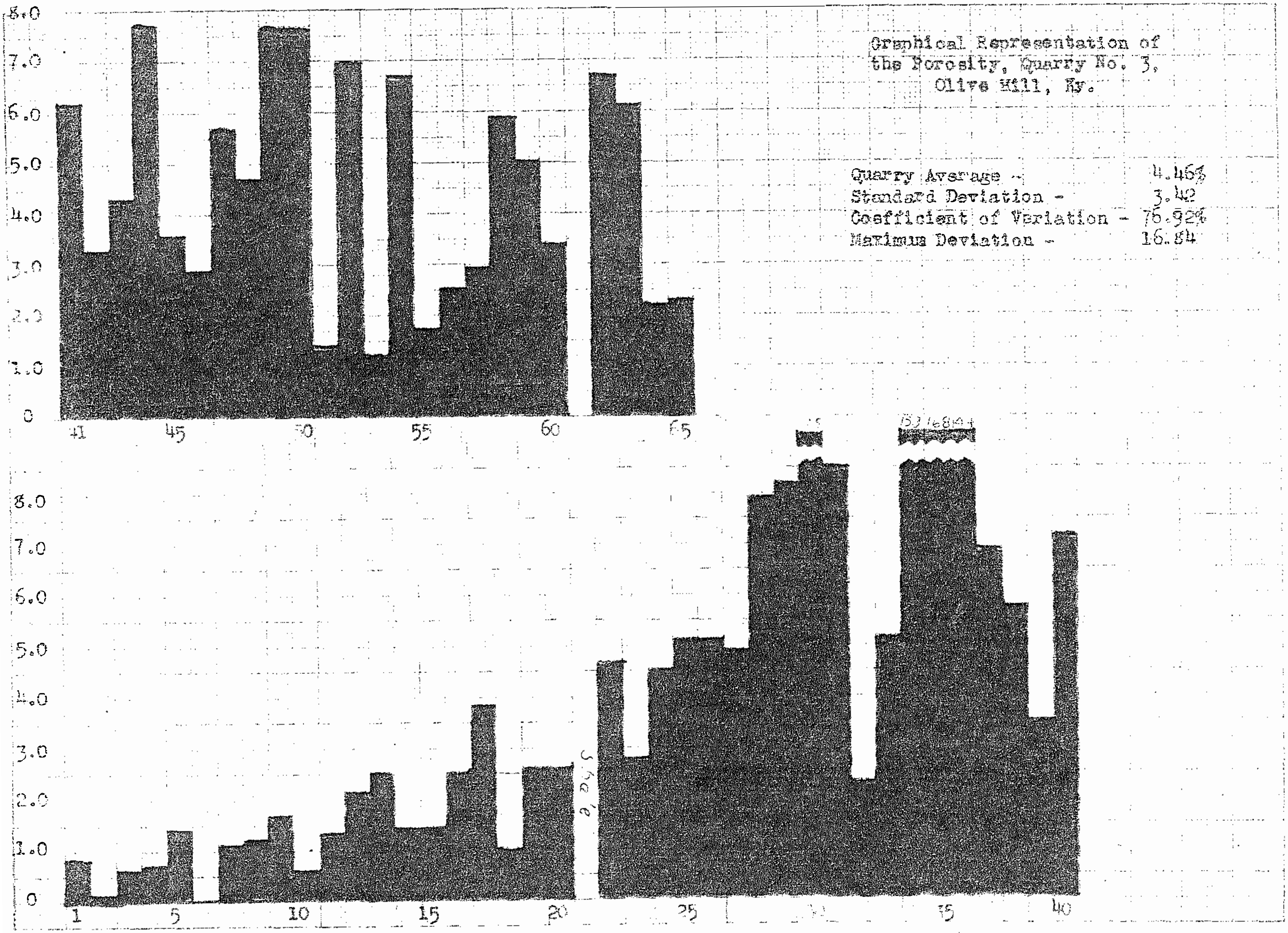


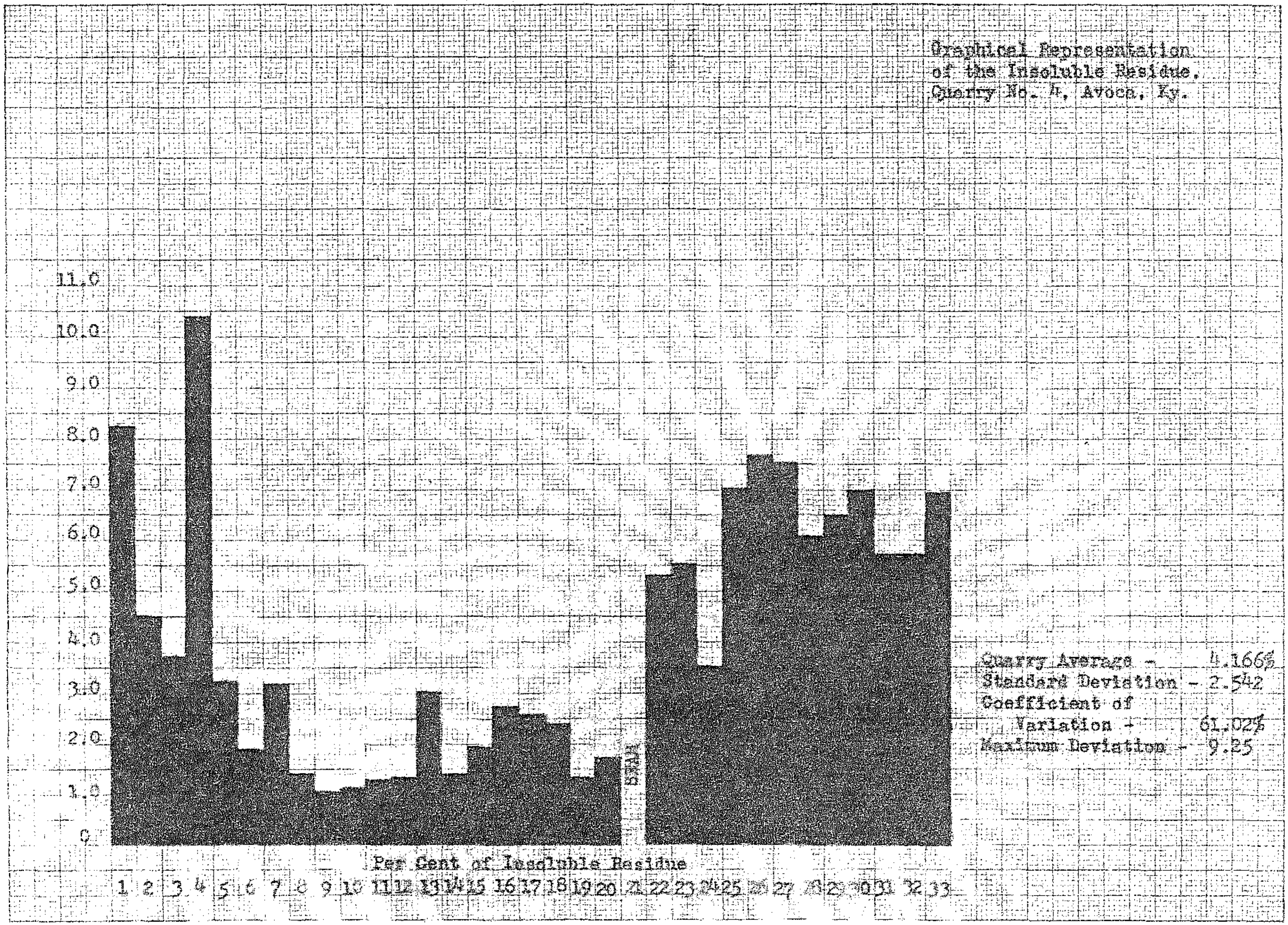
Permeability (in millidarcys) - Quarry No. 3

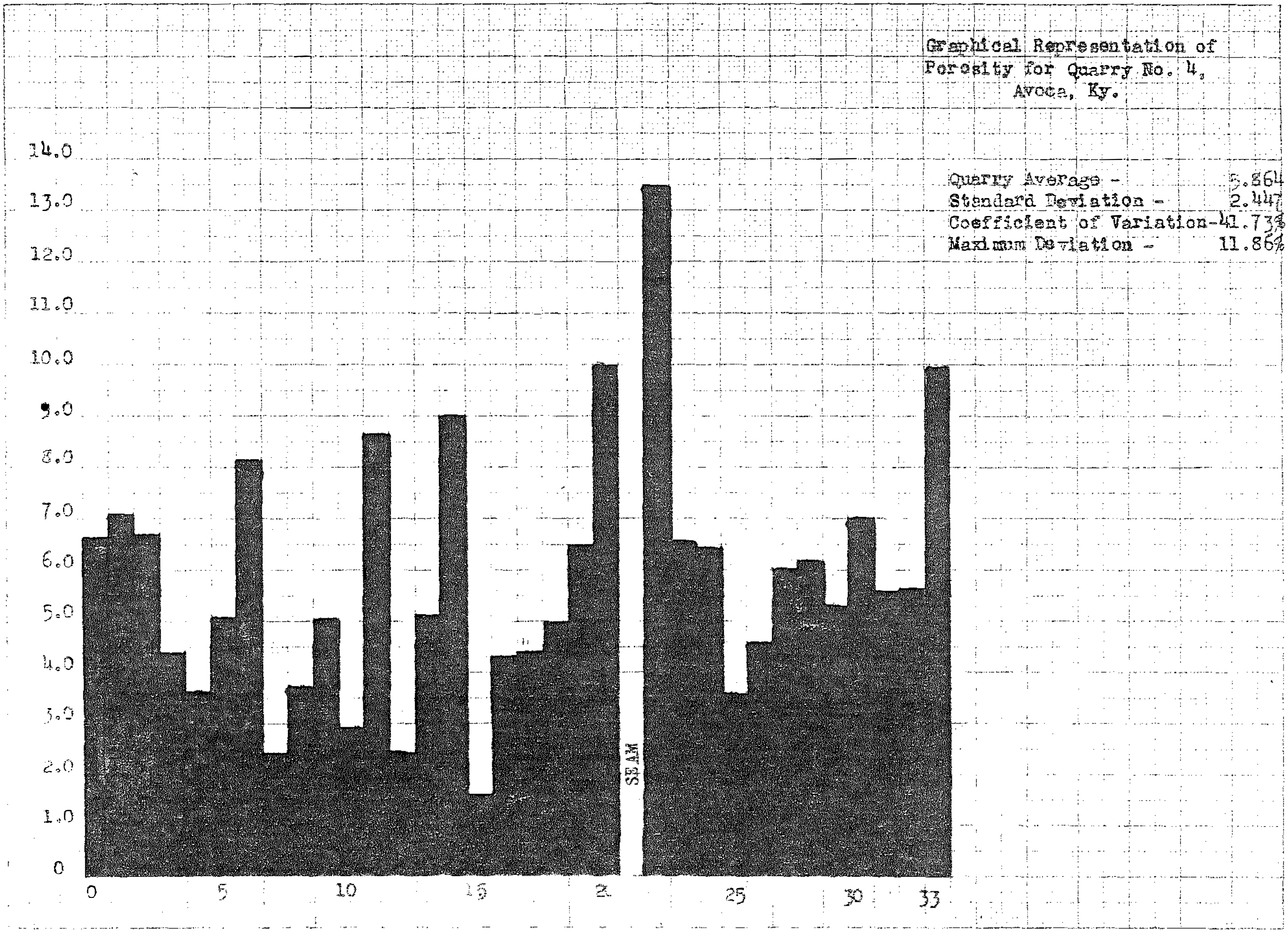


Absolute Specific Gravity, Quarry No. 3


Graphical Representation of the Insoluble Residue, Quarry No. 3, Olive Hill, Ky.
Quarry Average - 11.90
Standard Deviation - 8.63
Coefficient of Variation - 72.5%
Maximum Deviation - 58.0
20.0
15.0
10.0
5.0
0
Level 36
40
45
50
55
60
65
20
15
10
5
0
Level 1
5
10
15
35


Graphical Representation of
the Porosity, Quarry No. 3,
Olive Hill, Ky.
Quarry Average - 4.46%
Standard Deviation - 3.42
Coefficient of Variation - 76.92%
Maximum Deviation - 16.84
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
41
45
50
55
60
65
1
5
10
15
20
25
35
40


Graphical Representation
of the Insoluble Residue,
Quarry No. 4, Avoca, Ky.
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
Per Cent of Insoluble Residue
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33
Quarry Average - 4.166%
Standard Deviation - 2.542
Coefficient of
Variation - 61.02%
Maximum Deviation - 9.25



Porosity - Quarry No. 4


Graphical Representation of
(1) Absolute Specific Gravity,
(2) Bulk Specific Gravity, and
(3) Permeability of Quarry
No. 4, Avoca, Ky.
(1) Quarry Average - 2.8453
Standard Deviation - .143
Coefficient of Var.- 5.03%
Maximum Deviation - .1623
Absolute Specific Gravity - Quarry No. 4
(2) Quarry Average - 2.577
Standard Deviation - .105
Coefficient Var. - 3.92%
Maximum Deviation - .32
Bulk Specific Gravity - Quarry No. 4
(3)
Quarry Average - 1.876
Standard Deviation - 5.68
Coefficient Var. - 302.8
Maximum Deviation- 29.890
Average Permeability - Quarry No. 4 (in Millidarcys)
Level 0 5 10 15 20 25 30 33