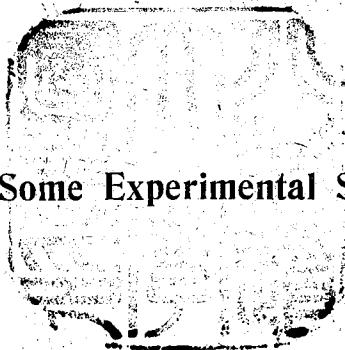




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Some Experimental Studies on "Hydro-expansion" of Clay.

By

Tadao HUKUTOMI.

(Received Aug. 1940).

CONTENTS.

	Page
Preface	388
Part I. General Remarks	389
Chapter I. The Motive for these Studies	389
Chapter II. Outline of Field-work	391
Chapter III. Preparations for these Experiments	393
Chapter IV. Moisture Content and Chemical Composition of the Clay in Tanna Tunnel	394
(A) Moisture Content of the Clay in Natural State	394
(B) Chemical Composition of the Tanna Tunnel	396
Part II. Preliminary Tests	398
Chapter I. Preliminary Tests on Hydration of Clay	398
(A) Observations on Relationship Between Clay and Aqueous Vapour	398
(B) Observations on Relationship Between Clay and Liquid Water	404
Chapter II. Preliminary Tests on Hydraulic Volume Changes of several Initially Compressed Clay	408
Part III. Main Experiments	412
Chapter I. Relationship Between E("Hydro-expansion") and C(Initial Compression Given to Test Material)	412
Chapter II. Relationship Between E("Hydro-expansion") and Q(Quantity of Test Material)	418
Chapter III. Relationship Between E("Hydro-expansion") and P(Applied Compression on Test Piece During Hydration)	421
Chapter IV. Relationship Between E("Hydro-expansion") and S(Powder-block Size of Test Material)	425
Chapter V. Relationship Between E("Hydro-expansion") and K(Kind of Test Material)	429
Chapter VI. Relationship Between E("Hydro-expansion") and Testing Conditions	433
Appendix. Experimental Formulae	453
Post-test. (I) "Hydro-expansion" of Clay for Different Temperatures of Hydration.	456
(II) "Hydro-expansion" of Clay and Other Materials	459

PREFACE.

It is well known that so-called "earth-pressures" appears in some tunneling works or in some mining works and leads into unexpected difficulties. These typical examples were recorded in Tanna tunnel, Atami line and in Hanaoka mine, Akita Prefecture. All of these pressures are even now explained only as effects of gravity.

But there are several questionable subjects connected with these "earth-pressures" within some wet clayish zones or masses, in which one finds some enormous powerful stress upon the entire cutting surfaces of tunnels.

The writer of this paper, who has long been interested in any topics concerning underground water, believes that so-called "earth-pressures" within such wet clayish zones or masses contain some unknown facts other than those which can be explained only by the gravitative efficient causes. That is, there must be found something to refer to the qualities of water and clay themselves in such cases. Therefore, the writer attempted an experimental study on "Hydro-expansion" of clay.

The term, "Hydro-expansion" means increase of the total apparent volume of some materials accompanied by absorbing water. In fact, one will recognize that any dry clay shows "Hydro-expansion" when it has been intensely compressed and then absorbs some water.

And the experiments teach one that the power which appears during "Hydro-expansion" is so enormous as to displace even strong timbering in a tunnel. The writer calls such power "Hydro-expansive power" in this paper.

Part I. GENERAL REMARKS.

Chapter I. THE MOTIVE FOR THESE STUDIES.

These studies were suggested by some questions about the so-called "earth-pressure" in the clay zone of Tanna tunnel, Atami line. The clay zone cropped out when the bottom heading working face reached 8,264 feet from the east cardinal point on the Atami side, November, 1925. A few days after the clay zone was excavated, the so-called "earth-pressure" appeared gradually in the tunnel, and the timbering work was destroyed by its influence. This pressure, the author believed at that time, was not so simple as every one had considered up to the present.

The clay at first when it occurred in the tunnel was compressed in dry state, and had some hardness and toughness. It seemed to have good geological condition, and was easily handled in the zone, through which no water penetrated like a concrete dam. Therefore all of the engineers and laborers had been very glad, before they knew the enormous power of its "earth-pressure". This clay was like a bad devil, who put on a gentle mask in the dark ground.

Mr. Seinosuke Okano, Chief Engineer of the tunnelling work on the Atami side related his several trial excavations in this clay zone.

(1) Normal timbering, using pine tree timbers each 6-8 inches in diameter and boards of the same material each 1.2 inches in thickness was easily destroyed.

(2) Next, the above normal timbering was strengthened by 6 feet span arch-formed concrete-blocks of 1 foot in thickness, between points 8,200-9,000 feet the east cardinal point of Atami side.

(3) Restrengthened inner wall of the above timbering work with 30-pound-rails.

All of them are not strong enough to resist the "earth-pressure" of clay.

The course of the tunnel was altered and an attempt made to find some new indirect branch route.

Again, however, the clay zone situated on the new line, appeared to be the same body, continuous with the first zone. This time, the usual timbering was abandoned from the beginning and iron material was used.

(4) I-beams, 5×6 inches were used. Here the engineers found upward creaping from the bottom at first, the "earth-pressure" of the walls became large, and the whole tunnel became dangerous in the end. The design in this case might resisted a compressive power of 20 pounds per square inch at least.

(5) Shields were used in wet muddy part of the clay zone. They were tried on the other line, the drainage tunnel, in the fluid clay zone. The shield was fitted together each segment to withstand 30 pounds pressure per square inch. But these were compressed flat by the "earth-pressure", and danger arose also in this cases.

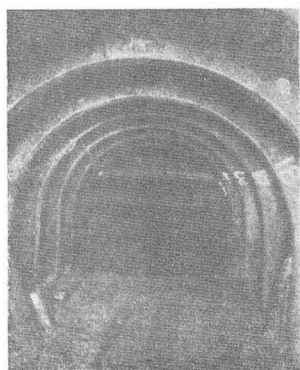
(6) Again the retaining walls were strengthened with cacrete-blocks in the inner side of the shields.

The final results were all the same and caused the engineers, who had engaged in the battle against the "earth-pressure" in the clay zone to know that even an endless long time, great human power and a large amount of expense were no use for this war, but only all in vain.

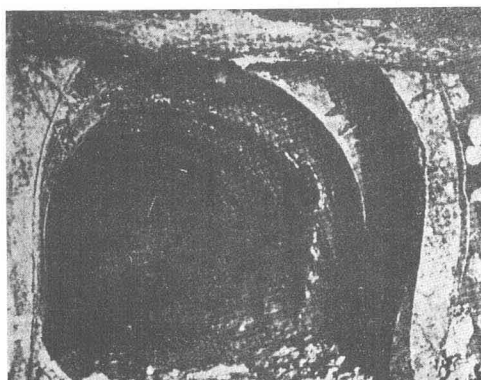
Next Plates (Pl. I—Pl. III') show some operational aspects in the clay zone, at the point 8,900 feet and nearby part of East (Atami) side. All of the timbering works are constructed of iron material. Plates I, II and III are pictures showing the normal constructions before the "earth-pressure" appeared in the tunnel and plates I', II' and III' show how these were deformed by the "earth-pressure" in the clay zone.

Thus it seemed that the clay zone would prove an insuperable varrier to the construction of the tunnel.

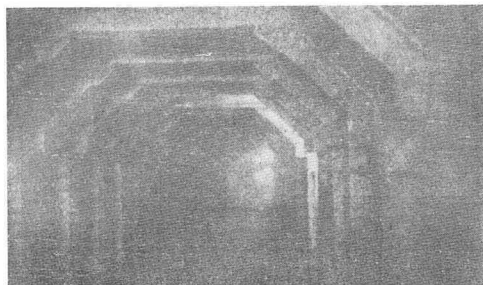
The present writer's observations at the spot on the "earth-pressure", aroused some question on the relationships between clay and water.



Pl. I. 30-pound-rail- timbering work in normal state.



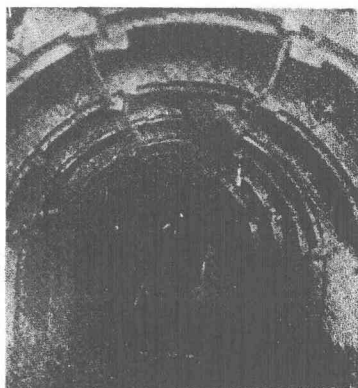
Pl. I'. The rails bent by "earth-pressure".



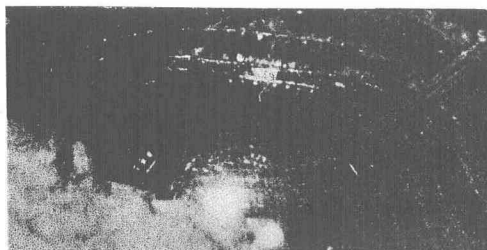
Pl. II. I-beam timbering work in normal state.



Pl. II'. The construction deformed by "earth-pressure."



Pl. III. Normal construction of shields.



Pl. III'. Segments of the shields buckled by "earth-pressure".

The facts, which he could find in the tunnel, were as follows:

(1) The clay was compressed and occurred in dry state, when it was excavated at first.

(2) No deformation or change in volume was found for a long time, if the material was kept in the same state.

(3) After a few days when it was excavated, and if it absorbed water then the "earth-pressure" appeared gradually (not so suddenly as "Bergschlag").

(4) Its thrust on timbering might be 8,000 pound (about 4 tons) per square foot and more. But the highest limit of the "earth-pressure" was absolutely unknown in tunnel.

Accordingly, where the clay in question occurred in the tunnel the fearsome powerful "earth-pressure" appeared when it absorbed water. Thus, the writer was led to study the relationship between clay and water in line his long interest in any subjects connected with "underground water".

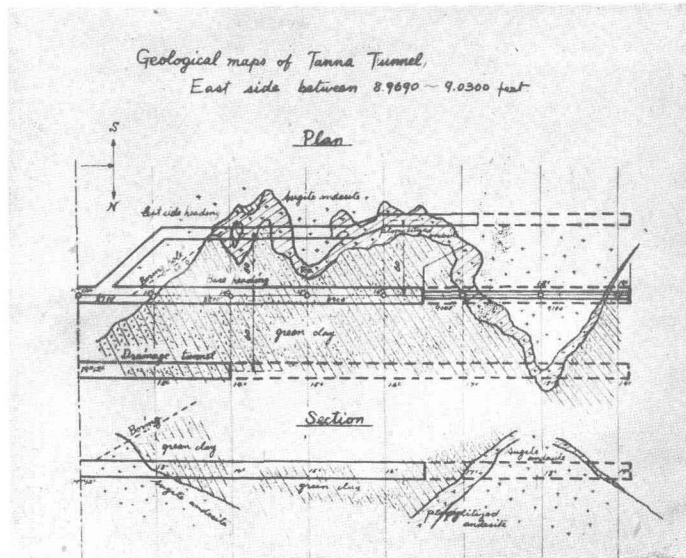
Chapter II. OUTLINE OF FIELD-WORK.

Observations on the mode of occurrence of this clay were carried on from the beginning to the end, while the tunnel was excavated through its zone. A geological map of the tunnel was made at last as in Pl. IV.

Another field-work was the measurement of humidity, observed by a standard hygrograph for a week. The humidity was found to be constant in the tunnel (between 8,969-9,030 feet), 97-100%.

The temperatures of water and air were recorded for the same days by a thermograph at the same place. The former was 19°C and the latter also almost constant 19°-20°C.

Then the clay was taken as samples several times to study in the laboratory. The samples were cut off carefully in uniform size (each 1 cubic foot) and packed in a few sealed boxes in site at once, and sent to the laboratory.



Pl. IV. Geological Map of the Tunnel.

Most of them were chosen in the tunnel between the points of 19 miles 15 chains to 19 miles 16 chains 30, but some were for reference taken from the outcrop of the clay on the surface (Nonakayama) in the vicinity of this tunnel.

In connection with the above statements, some uniformation on the geological occurrence of this questionable clay is pertinent.

(1) The clay is a kind of some residual clay, within which augite andesite and its tufaceous agglomerate have been attacked by hydrothermal action in site.

(2) The effect of hydrothermal action extended mostly along some weak portion (that is, cracks, fissures; faults or other crushed zone) in andesite and agglomerate.

(3) Therefore, this clay distributes in the tunnel as some irregular masses, but its general form may be a continuous great zone connected underground.

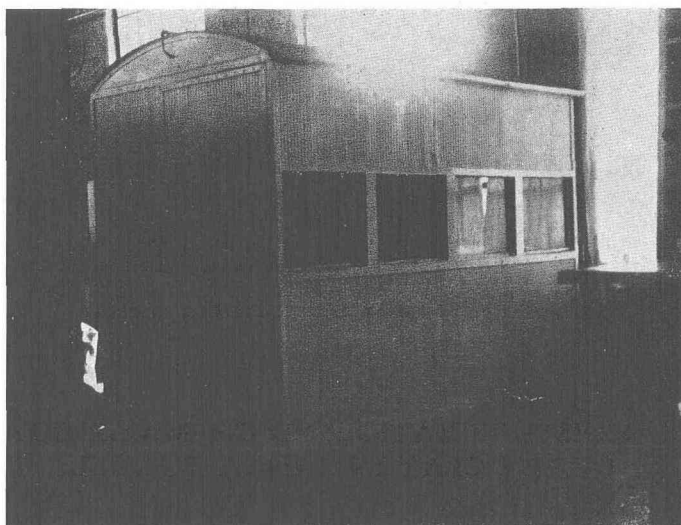
(4) The boundary between the clayish part and unchangable part of andesite and agglomerate is mostly indistinct, but is sometimes distinct with a sharp plane, like a fault scarp.

(5) Some underground water can be found within the clay zone, through which a fault has sometime cut and disturbed its structure. But there is only a small quantity of water in it, when the clay is kept in normal state.

Chapter III. PREPARATIONS FOR THESE EXPERIMENTS.

At first, a small special chamber, in which these experiments would be carried on, was built in the laboratory. The author could make the conditions (humidity; temperature; darkness; etc.) in the chamber like those in the tunnel, if necessary.

This chamber is still used as a dark-room for some other purpose. Its base-area is $2. \times 1.45$ m. and the height of its inner side is 1.9 m., constructed of iron plates with four windows on one side and a door on another side. (See Pl. V.)



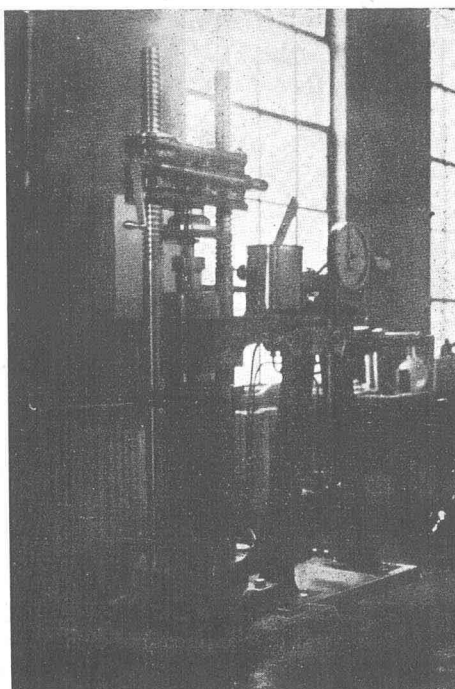
Pl. V. The small special chamber in which most of these experiments were carried on in the laboratory.

In this chamber, while the experiments were carried on, almost all the necessary articles were arranged; for example, an aqueous vapour generator and a hydrograph; an electric heater and a thermograph etc.

Other preparations for these experiments includes a compression testing machine, which was used to make the test pieces of clay. (See Pl. VI.)

Many new apparatuses were made for special purposes for these studies, but among them a few have finally served.

They will be described afterwards as necessary.



Pl. VI. The 60-ton-compression testing machine.

Chapter IV. MOISTURE RATIO AND CHEMICAL COMPOSITION OF THE CLAY IN TANNA TUNNEL.

(A) Moisture Content of the Clay in Natural State.

- a) *Samples of clay taken in Tanna tunnel, April, 1930 and kept at original compression.*

Table 1.

Nos. of samples and points where they were taken.	Weight of samples, at first.	Weight after dehydration.	Diminished weight.	Percentage of moisture.
No 1. Outer wall of main route (a)	gr. 20.00	gr. 18.00	gr 2.00	gr. 10.00
No. 2. Ditto. (b)	20.00	17.50	2.50	12.50
No. 3. Ditto. (c)	20.00	17.50	2.50	12.50
Average				11.67

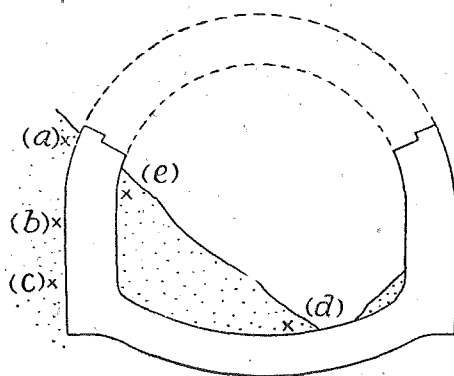
Table 1.—(Continued)

Nos. of samples and points where they were taken.	Weight of samples, at first.	Weight after dehydration.	Diminished weight.	Percentage of moisture.
No. 4. Inner side of main route (d)	gr. 20.00	gr. 16.50	gr. 3.50	% 17.50
No. 5. Ditto. (e)	20.00	17.75	2.25	11.25
Average				14.37
No. 6. Outer wall of branch route (f)	20.00	17.75	2.25	11.25
No. 7. Ditto. (g)	20.00	17.50	2.25	12.50
No. 8. Ditto. (h)	20.00	16.00	4.00	20.00
No. 9. Ditto. (i)	20.00	16.70	3.30	16.50
Average				15.06

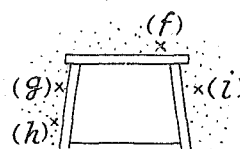
b) *Samples of somewhat wet loose Clay, which exhibited "earth-pressure" in Tanna tunnel, April, 1930.*

Table 2.

Nos. of samples and points, at where they were taken.	Weight of samples, at first.	Weight after dehydration.	Diminished weight	Percentage of moisture.
No. 10. Outer wall of a branch route (f)	gr. 10.00	gr. 7.55	gr. 2.45	% 24.50
No. 11. Ditto. (g)	10.00	7.40	2.60	26.00
No. 12. Ditto. (h)	10.00	7.00	3.00	30.00
No. 13. Ditto. (h)	10.00	6.60	3.40	34.00
No. 14. Ditto. (i)	10.00	7.10	2.90	29.00
No. 15. Ditto. (i)	10.00	7.20	2.80	28.00
No. 16. Ditto. (i)	10.00	7.05	2.95	29.50
Average				28.71



Main tunnel.



Branch route.

Pl. VII. A cross section, cut through a part of the main Tanna tunnel and a branch route. The points (a)-(i) show several places, where the samples of clay have been taken.

In making these measurements, dehydration of clay was very delicate. After many tests, the samples were put in an Acme electric heater kept at 90°-100°C. temperature for 8 hours and then in a desiccator for 24 hours. These temperatures and time were, the writer found, absolutely necessary for bringing 10-20 gr. of the clay to a constantly dry state.

Now according to the above data, something is known of the moisture conditions of the clay in natural state.

(1) The moisture content of the lower part of the clay is larger than that of the upper.

(2) The average moisture content of the clay around the branch route is larger than that of the main tunnel side.

(3) The percentage of moisture of the clay taken and kept at its initial compression in the tunnel is 10.00-20.00% but the somewhat wet loose clay in which the "earth-pressure" has already begun to appear is 24.50-34.00%.

These measurements give one some idea about certain natural conditions of the clay in the tunnel, on which some investigations will be reported later.

(B) Chemical Composition of the Clay in Tanna Tunnel.

Samples of the clay in Tanna tunnel, taken at points between 19 miles 15 chains and 19 miles 16 chains 30.

Table 3.

Nos. of samples.	No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	Average
	%	%	%	%	%	%
SiO ₂	70.68	62.59	62.45	65.81	61.77	64.62
Al ₂ O ₃	9.82	12.14	8.94	13.89	11.98	11.35
Fe ₂ O ₃	7.06	7.54	8.82	1.64	5.87	6.19
CaO	0.89	1.10	1.13	2.18	0.99	1.24
MgO	2.49	2.73	4.96	1.92	2.26	2.87
P ₂ O ₅	0.24	0.21	0.21	tr.	0.13	0.16
MnO	0.22	0.36	0.28	0.16	0	0.20
K ₂ O					2.89	
Na ₂ O	0.22	5.88	7.76	2.46	8.94	5.63
Cl	—	—	—	—	0	0
S	0.15	0.05	0.34	0.04	0.03	0.12
SO ₃	—	—	—	—	1.02	1.02
Ignition lose	2.62	6.98	5.22	10.86	6.32	6.40
Total	100.39	99.58	100.11	99.98	100.98	

Chemical composition of the above samples was analyzed by Mr. Kakiti Hayashi, Engineer of Hokkaido-tio.

At several outcrops of the surface residual clay attacked by hydrothermal action, many fine gypsum crystals are seen by naked eyes. Hot springs surrounding these outcrops of clay contain a large quantity of CaSO_4 . Therefore, hydration or dehydration may, the writer has supposed, exert some influence on crystalline water of gypsum or such other easily soluble matters. According to the above analyses, however, the quantity of CaO or SO_3 is negligibly small and other soluble composition in cold water is also small. These facts teach one that the volume change of the clay by hydration or dehydration may be summarized as follows: "negligibly little or no chemical action occurs in this case at least, and physical action, such as capillarity etc., must mostly relate it." These considerations will be examined afterward and next the experimental works carried on in the laboratory will be described.

Part II. PRELIMINARY TESTS.

Chapter I. PRELIMINARY TEST ON HYDRATION OF CLAY.

The above described measurements showed that the initially compressed clay in natural state had obtained 10–20% of water in Tanna tunnel and the somewhat wet clay 24.50–34.00%. The clay in the tunnel, therefore, gains much water after a few days and the so-called “earth-pressure” appears gradually in its wet part. It is known that aqueous vapour is full or saturated (100%) in the tunnel and liquid water (underground water) is also plentiful around the clay zone. Then in what state is the water by which the clay becomes wet, aqueous vapour or liquid water?

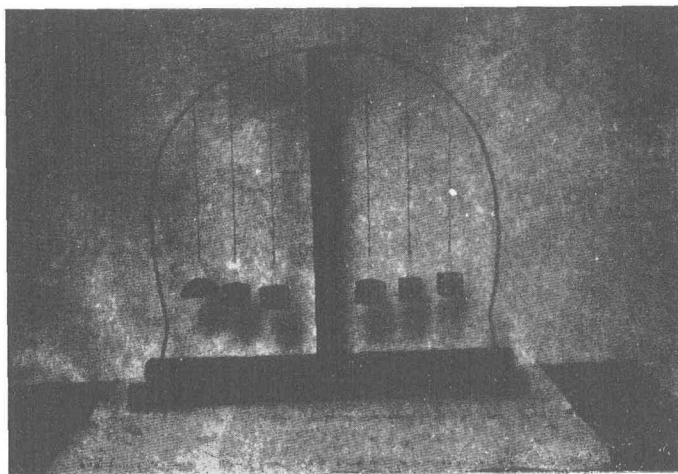
The above questions will be taken up as follows:

- (A) The relationship between the clay and aqueous vapour;
- (B) The relationship between the clay and liquid water.

These relationships were observed in the small special chamber which was already been described.

(A) Observations on the Relationship Between the Clay and Aqueous Vapour.

Observation method—Samples were hung down by fine silk threads in the small special chamber, in which aqueous vapour was almost full (90–100% humidity recorded by a hygograph).



Pl. VIII. Samples hanging in the small chamber full of aqueous vapour.

(a) "Hydration" (Absorbing Aqueous Vapour) -Test of Clay-Blocks
Taken in Natural State.

Table 4.

Nos. of samples.	No. 1.	No. 2.	No. 3.	No. 4.
Weight of samples taken at first.	gr. 135.0	gr. 100.0	gr. 84.0	gr. 77.0
Weight after 1 hr. and "Hydrous Ratio".	135.0+1.0 0.75%	100.0+1.0 1.00%	84.0+0.8 0.95%	77.0+0.6 0.78%
After 2 hours.	136.0+0.5	101.0+0.2	84.8+0.1	77.6+0.35
After 3 hours.	136.5+0.	101.2+0	84.9+0.3	77.95+0.05
After 4 hours.	136.5+0.7	101.2+0.7	85.2+0.4	78.0+0.3
After 5 hours.	137.2+0.4 1.92%	102.0+0.1 2.00%	85.6+0 1.90%	78.4+0.3 2.26%
After 6 hours.	137.7+0.1	102.1+0.2	85.6+0.2	78.7+0
After 7 hours.	137.7+0.4	102.1+0.2	85.8+0.3	78.7+0.1
After 8 hours.	138.1+0.2	102.3+0.3	86.1+0.2	78.8+0.2
After 9 hours.	138.3+0.1	102.6+0.05	86.3+0.05	79.0+0.1
After 10 hours.	138.4+0.2 2.60%	102.7+0.1 2.80%	86.35+0.25 3.09%	79.1+0.1 2.11%
After 11 hours.	138.6+0.4	102.8+0.3	86.6+0.1	79.2+0.2
After 12 hours.	139.0+0.3	103.1+0.3	86.7+0.3	79.4+0.2
After 13 hours.	139.3+0.4	103.4+0.3	87.0+0.2	79.6+0.2
After 14 hours.	139.7+0.1	103.7+0.1	87.2+0.1	79.8+0
After 15 hours.	139.8+0.2 3.73%	103.8+0.2 4.00%	87.3+0.1 3.92%	79.9+0.4 3.76%
After 16 hours.	140.0+0.3	104.0+0.2	87.4+0.2	79.9+0.4
After 17 hours.	140.3+0.3	104.2+0.2	87.6+0.1	80.3+0.1
After 18 hours.	140.6+0.2	104.4+0.2	87.7+0.1	80.4+0.1
After 19 hours.	140.8+0.2	104.6+0.2	87.8+0.2	80.5+0.2
After 20 hours.	141.0+0.1 4.51%	104.8+0.1 4.90%	88.0+0.2 5.00%	80.7+0 4.80%
After 21 hours.	141.1+0.2	104.9+0.1	88.2+0.2	80.7+0.2
After 22 hours.	141.3+0.4	105.0+0.3	88.4+0.3	80.9+0.4
After 23 hours.	141.7+0.3	105.3+0.4	88.7+0.1	81.3+0
After 24 hours.	142.0+0.2	105.7+0.1	88.8+0.2	81.3+0.2
After 25 hours.	142.2+0.3 5.55%	105.8+0.4 6.20%	89.0+0.3 6.30%	81.5+0.7 6.75%
After 26 hours.	142.5+0.3	106.2+0.3	89.3+0.2	82.2+0.2
After 27 hours.	142.8+0.1	106.5+0.1	89.5+0.5	82.4+0.1
After 28 hours.	142.9+0.4	106.6+0.4	89.7+0.3	82.5+0.2
After 29 hours.	143.3+0.3	107.0+0.3	90.0+0.3	82.7+0.2
After 30 hours.	143.6+0.2 6.51%	107.3+0.2 7.50%	90.3+0.3 7.85%	82.9+0.4 8.18%

Table 4.—(Continued)

Nos. of samples.	No. 1.	No. 2.	No. 3.	No. 4.
After 31 hours.	143.8+0.2	107.5+0.1	90.6+0.1	83.3+0.1
After 32 hours.	144.0+0.2	107.6+0.2	90.7+0.1	83.4+0.0
After 33 hours.	144.2+0.5	107.8+0.6	90.8+0.4	83.4+0.4
After 34 hours.	144.7+0.3	108.4+0.4	91.2+0.2	83.8+0.2
After 35 hours.	145.0+0.5 7.92%	108.8+0.2 9.00%	91.4+0.4 9.29%	84.0+0.3 9.48%
After 36 hours.	145.5+0.5	109.0+0.1	91.8+0.1	84.3+0.1
After 37 hours.	146.0+0	109.1+0.1	91.9+0	84.4+0
After 38 hours.	146.0+0.1	109.2+0.1	91.9+0.2	84.4+0.2
After 39 hours.	146.1+0	109.3+0	92.1+0	84.6+0
After 40 hours.	146.0+0 8.22%	109.3+0.2 9.50%	92.1+0.1 9.76%	84.6+0.1 10.00%
After 41 hours.	146.1+0	109.5+0	92.2+0	84.7+0
After 42 hours.	146.1+0	109.5+0.2	92.2+0	84.7+0.1
After 43 hours.	146.1+0	109.7+0	92.2+0	84.8+0
After 44 hours.	146.1+0	109.7+0	92.2+0	84.8+0
After 45 hours.	146.1+0 8.22%	109.7+0 9.70%	92.2+0 9.76%	84.8+0 10.12%
After 50 hours.	146.1+0	109.7+0	92.2+0	84.8+0

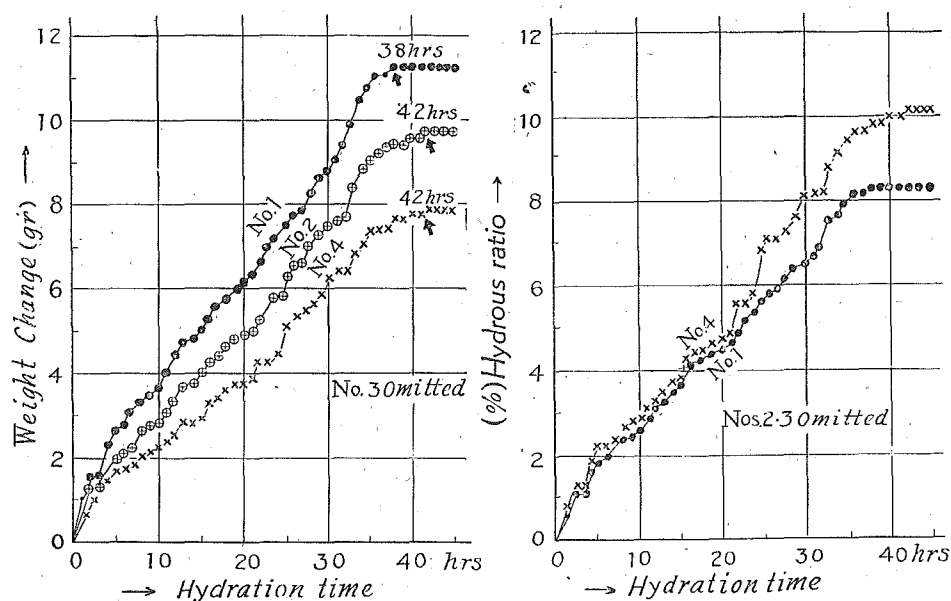


Fig. 1. Curves showing "Hydration" (absorbing aqueous vapour) of Tanna Clay in natural state. (see Table 4.)

(b) "Hydration" (Absorbing Aqueous Vapour) -Test of Powdered Clay,
Regularly Farmed by Compression.

Table 5.

Nos. of samples.	No. 6.	No. 7.	No. 8.	No. 9.	No. 10.	No. 11.
Weight of sample. taken at first.	gr. 53.10	gr. 52.75	gr. 52.80	gr. 45.30	gr. 38.20	gr. 36.90
Weight after 1 hr. and "Hydrous Ratio"	53.50 0.84%	53.15 0.75%	53.30 0.94%	45.80 1.10%	38.60 1.04%	37.30 1.08
After 2 hours.	53.60	53.40	53.50	46.00	38.70	37.50
After 3 hours.	53.80	53.60	53.65	46.10	38.85	37.70
After 4 hours.	53.90	53.80	53.75	46.40	39.05	37.90
After 5 hours.	64.00 1.79%	53.85 2.08%	53.90 2.68%	46.50 2.64%	39.20 2.61%	38.00 2.98%
After 6 hours.	55.00	54.00	54.00	46.60	39.70	38.10
After 7 hours.	54.25	54.30	54.50	46.95	39.50	38.40
After 8 hours.	54.40	54.45	54.50	47.10	39.60	38.55
After 9 hours.	54.50	54.70	54.60	47.15	39.65	38.60
After 10 hours.	54.60 2.92%	54.75 3.79%	54.70 3.59%	47.30 4.41%	39.65 3.79%	38.70 4.89%
After 11 hours.	54.75	54.85	54.90	47.50	40.10	39.20
After 12 hours.	54.85	55.00	55.00	47.70	40.30	39.50
After 13 hours.	54.95	55.20	55.20	47.80	40.50	39.90
After 14 hours.	56.00	55.25	55.25	47.85	40.55	39.95
After 15 hours.	56.00 3.86%	55.25 4.73%	55.25 4.64%	47.90 5.73%	40.55 6.15%	40.00 8.40%
After 16 hours.	55.15	55.40	55.40	48.00	40.60	40.05
After 17 hours.	55.20	55.40	55.40	48.00	40.70	40.10
After 18 hours.	55.35	55.60	55.60	48.25	40.80	40.10
After 19 hours.	55.45	55.70	55.70	48.35	40.90	40.20
After 20 hours.	55.55 4.71%	55.90 5.97%	55.85 5.77%	48.35 6.73%	41.10 7.59%	40.20 8.94%
After 21 hours.	55.65	55.95	55.85	48.45	41.10	40.20
After 22 hours.	55.65	56.10	55.90	48.50	41.10	40.30
After 23 hours.	55.70	56.10	56.10	48.55	41.25	40.40
After 24 hours.	55.80	56.20	56.15	49.85	41.25	40.40
After 25 hours.	55.95 5.46%	56.30 6.72%	56.30 6.62%	48.85 7.83%	41.25 7.98%	40.45 9.62%
After 26 hours.	56.00	56.40	56.40	48.90	41.35	40.50
After 27 hours.	56.10	56.50	56.45	48.90	41.40	40.55
After 28 hours.	56.15	56.50	56.45	49.00	41.50	40.60
After 29 hours.	56.15	56.55	56.50	49.00	41.50	40.65
After 30 hours.	56.40 6.31%	56.80 7.67%	56.75 7.48%	49.20 8.60%	41.60 8.90%	40.70 10.29%

Table 5.—(Continued)

Nos. of samples.	No. 6.	No. 7.	No. 8.	No. 9.	No. 10.	No. 11.
After 31 hours.	56.40	56.90	56.85	49.30	41.70	40.70
After 32 hours.	56.50	56.90	56.90	49.30	41.75	40.80
After 33 hours.	56.55	56.95	56.90	49.30	41.75	40.80
After 34 hours.	56.60	57.00	56.90	49.40	41.85	40.80
After 35 hours.	56.60 6.69%	57.10 8.24%	56.90 7.76%	49.40 9.05%	41.85 9.55%	40.85 10.70%
After 36 hours.	56.70	57.20	57.00	49.50	41.90	40.85
After 37 hours.	56.70	57.20	57.10	49.55	41.90	40.85
After 38 hours.	56.90	57.35	57.20	49.60	41.90	40.85
After 39 hours.	57.00	57.50	57.30	49.70	42.00	40.85
After 40 hours.	57.00 7.44%	57.50 9.00%	57.30 8.52%	49.70 9.71%	42.05 10.07%	40.85 10.70%
After 41 hours.	57.05	57.50	57.40	49.70	42.05	40.85
After 42 hours.	57.05	57.60	57.40	49.70	42.10	40.85
After 43 hours.	57.10	57.75	57.60	49.85	42.10	40.90
After 44 hours.	57.10	57.75	57.65	40.90	42.10	40.90
After 45 hours.	57.10 7.63%	57.80 9.57%	56.65 9.18%	50.05 10.48%	42.10 10.20%	40.95 10.97%
After 46 hours.	57.10	57.80	57.65	50.15	42.15	40.95
After 47 hours.	57.10	58.00	57.70	50.15	42.15	40.95
After 48 hours.	57.10	58.10	57.85	50.25	42.35	41.05
After 49 hours.	57.10	58.10	57.90	50.30	42.40	41.10
After 50 hours.	57.10	58.20 10.33%	57.95 9.75%	50.30 11.03%	42.40 10.99%	41.20 11.65%
After 51 hours.		58.20	57.95	50.40	42.50	41.20
After 52 hours.		58.25	57.95	50.40	42.50	41.20
After 53 hours.		58.30	58.10	50.40	42.50	41.20
After 54 hours.		58.45	58.20	50.55	42.50	41.30
After 55 hours.	57.10	58.65 11.18%	58.35 10.51%	50.64 11.81%	42.60 11.51%	41.30 11.92%
After 56 hours.		58.75	58.35	50.75	42.70	41.40
After 57 hours.		58.80	58.45	50.85	42.70	41.40
After 58 hours.		59.00	58.45	50.85	42.80	41.40
After 59 hours.		59.00	58.60	50.95	42.95	41.50
After 60 hours.	57.10	59.10 12.03%	58.75 11.26%	51.00 12.58%	42.95 12.43%	41.50 12.46%
After 61 hours.		59.20	58.75	51.10	42.95	41.55
After 62 hours.		59.20	58.75	51.10	42.95	41.55
After 63 hours.		59.30	58.80	51.20	43.00	41.55
After 64 hours.		59.40	58.85	51.20	43.10	41.55
After 65 hours.	57.10	12.60%	12.55%	13.02%	12.82%	12.60%

Table 5.—(Continued)

Nos. of samples.	No. 6.	No. 7.	No. 8.	No. 9.	No. 10.	No. 11.
After 66 hours.		59.40	58.95	51.20	43.10	41.55
After 67 hours.		59.45	58.95	51.20	43.10	41.55
After 68 hours.		59.45	58.95	51.30	43.10	41.55
After 69 hours.		59.65	58.95	51.30	43.10	41.55
After 70 hours.	57.10	59.65 13.08%	58.95 11.64%	51.30 13.24%	43.10	41.55
After 80 hours.	57.10	59.65	58.95	51.30	43.10	41.55

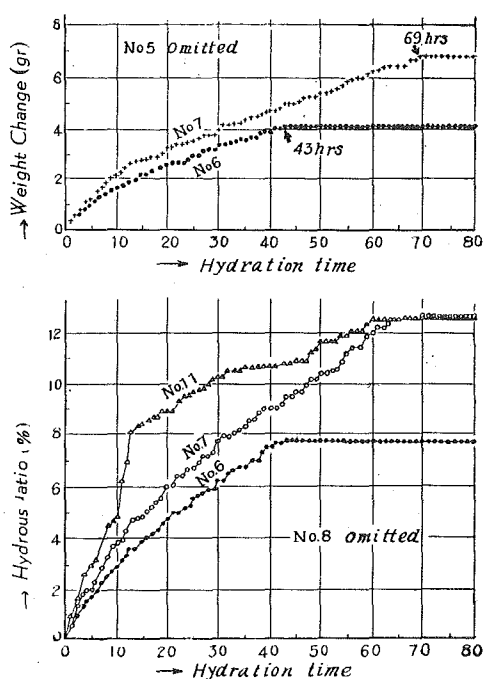


Fig. 2. Curves showing Hydration (absorbing aqueous vapour) of the Tanna powdered clay regularly formed by compression. (see Table 5.)

SUMMARY (A)

Observation on the relationships between the clay and aqueous vapour.

(1) "Hydration" (absorbing aqueous vapour) of the clay (a) in initially compressed natural state and also (b) in artificially compressed powdered state show almost similar results.

(2) Weight changes of the samples owing to this "hydration" continue gradually for a long time, and then stop.

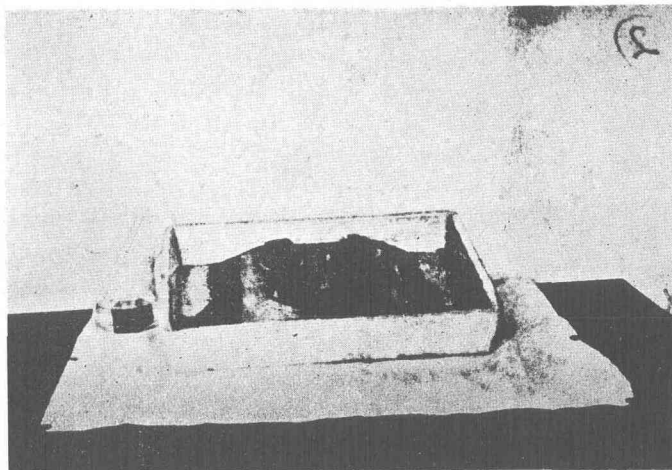
(3) The final "hydrous ratio" of each sample is questionable in this case. Because it can be recognized that all of these samples have not completely absorbed aqueous vapour, and the inner parts of them are still in dry state as before, while the outermost superficial parts are wet. These wet outer zones form thin layers (5-8 mm. in thickness) just like watertight films with microscopical bubbles among clay particles protected no longer against hydration. Therefore, at normal atmospheric pressure and temperature even 100% of aqueous vapour in the air is not be absorbed completely into clay.

Generally speaking, most weathered surfaces suffer, they say, the influence of aqueous vapour and so forth. But the influence of aqueous vapour at normal atmospheric pressure must be a fit topic to study experimentally.

The term "hydration" or "hydrous ratio" in this case, therefore, has not meant real complete hydration or hydrous ratio.

(B) Observation on Relationship Between Clay and Liquid Water.

Observation methods—(a') normal hydrous ratio measurement (that is, samples are put in water completely), and (b') they were allowed to absorb water from each one face, (that is, samples are put on wet quartz-sand layer covered by a sheet large filter paper and saturated with liquid water). (see Pl. IX)



Pl. IX. Hydration (absorbing liquid water) -test. Samples—equal samples as these of the above (A) test, (that is, each sample had been cut into two parts beforehand; each half part was employed for the former (A) test, each another half one utilized for this (B) observation).

(a') *Normal Hydrous Ratio Measurement of Initially Compressed Clay-Blocks Taken in Tanna Tunnel.*

Table 6.

Nos. of samples.	No. 1'.	No. 2'.	No. 3'.	No. 4'.	No. 6'.
Weight of samples taken at first.	gr. 133.0	gr. 98.8	gr. 83.3	gr. 76.4	gr. 53.0
Weight after 1 hr. and Hydrous Ratio (%)	142.0 6.76%	107.1 8.40%	90.3 8.40%	83.0 8.63%	56.5 6.60
After 2 hours.	143.7	108.6	91.4	84.4	57.0
After 3 hours.	144.5	109.3	92.0	84.7	57.1
After 4 hours.	145.2	109.3	92.1	84.7	57.2
After 5 hours.	145.6 9.47%	109.3 10.62%	92.1 10.56%	84.7 10.86%	57.2 7.92%
After 6 hours.	146.0	109.3	92.1	84.7	57.2
After 7 hours.	146.0	109.3	92.1	84.7	57.2
After 8 hours.	146.0	109.3	92.1	84.7	57.2
After 9 hours.	146.0	109.3	92.1	84.7	57.2
After 10 hours.	146.0 9.77%	109.3	92.1	84.7	57.2
After 11 hours.	146.0	109.3	92.1	84.7	57.2
After 12 hours.	146.0	109.3	92.1	84.7	57.2

All of the samples were examined after 48 hours and after 72 hours, but no change was recognized.

Next curves show the above results (see Table 6).

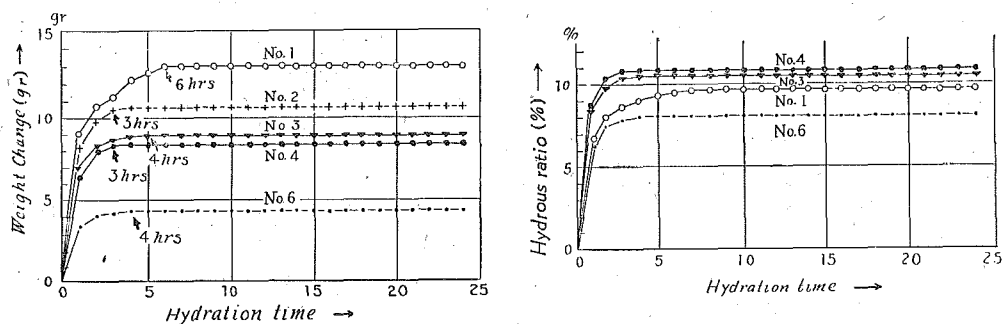


Fig. 3. Curves showing Hydration (absorbing liquid water) -test of the Clay-blocks in natural state. (see Table 6.)

(b') *Hydration (Absorbing Liquid Water) of the Powdered Clay Regularly Formed by Compression, Absorbing Water from one Face.*

Table 7.

Nos. of samples.	No. 7'.	No. 8'.	No. 9'.	No. 10'.	No. 11'.
Weight of samples taken at first.	gr. 52.6	gr. 52.7	gr. 45.2	gr. 38.0	gr. 36.8
Weight after 1 hr. and Hydrus Ratio (%)	58.9 11.97%	59.0 11.95%	56.5 25.00%	49.9 31.31%	46.6 26.63%
After 2 hours.	64.6	64.3	63.0	53.4	50.4
After 3 hours.	64.75	64.45	63.4	53.6	50.6
After 4 hours.	64.75	64.45	63.5	53.7	50.65
After 5 hours.	64.75 23.09%	64.45 22.29%	63.7 40.92%	53.9 41.84%	50.65 37.63%
After 6 hours.	64.75	64.45	63.9	53.9	50.65
After 7 hours.	64.75	64.45	63.9	53.9	50.65
After 8 hours.	64.75	64.45	63.9	53.9	50.65
After 9 hours.	64.75	64.45	63.9	53.9	50.65
After 10 hours.	64.75	64.45	63.9 41.37%	53.9	50.65
After 11 hours.	64.75	64.45	63.9	53.9	50.65
After 12 hours.	64.75	64.45	63.9	53.9	50.65
After 48 hours.	64.75	64.45	63.9	53.9	50.65
After 72 hours.	64.75	64.45	63.9	53.9	50.65

In this case, Nos. 7'-11' of samples deformed and their volume-changes appeared.

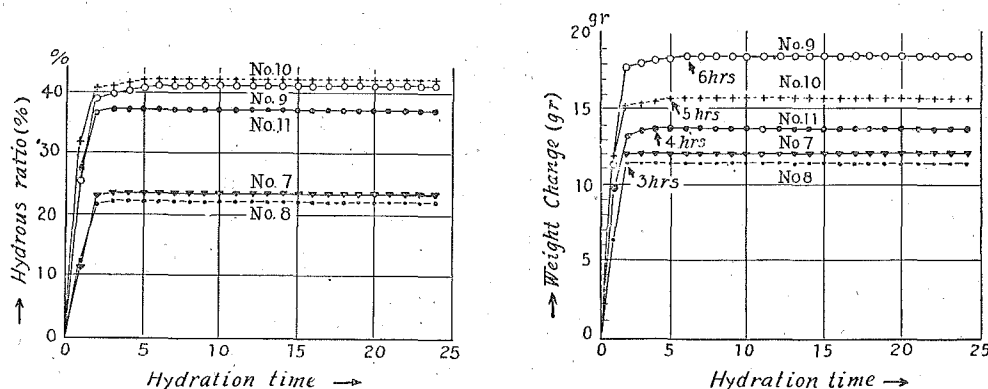


Fig. 4. Curves showing Hydration (absorbing liquid water) -test of powdered Clay regularly formed by compression. (see Table 7.)

SUMMARY OF (B).

Observation on the relationships between the clay and liquid water.

(1') Hydration (absorbing liquid water) -tests of the clay (a') in initially compressed natural state, and (b') in artificially compressed powdered state show almost similar results.

(2') Weight changes of the samples owing to hydration (absorbing liquid water) occur suddenly for short time, and then stop.

(3') These hydrous ratios (B,b') are larger than those in the former case (A,b).

(4') Inner parts of each sample are the same as their outer surface in wetness.

(5') Volumes of Nos. 7'-11' of samples expand apparently as follows :

Table 8. Volume-change due to Hydration.

Nos. of samples.	No. 7'.	No. 8'.	No. 9'.	No. 10'.	No. 11'.
Volume-change (original forms) (29 mm ³ .)	$+(2.5 \times 1.5 \times 0.5)$	$+(2.5 \times 2.0 \times 0.5)$	$+(3.5 \times 2.0 \times 5.0)$	$+(3.0 \times 1.5 \times 6.0)$	$+(16 \times 4.0 \times 0.5)$
"Volume-expansion" Ratio (%)	0.0073	0.0099	0.0186	0.0121	0.2961

CONCLUSIONS TO THIS CHAPTER. (HYDRATION PRELIMINARY TESTS OF CLAY).

In this chapter observations have been made (A) on the relationship between the Tanna tunnel clay and aqueous vapour and (B) on the relationship between the clay and liquid water. Comparison between the above (A) and (B) observations may be summarized in the following Table 9.

As seen from those observations, a certain elementary knowledge about the relationships among the clay and aqueous vapour and liquid water in limited conditions has been obtained.

(A) The clay absorbs aqueous vapour, but it needs a rather long time and moreover its "hydration" stops in normal atmospheric pressure and temperature before the inner part of the sample becomes completely wet as on its surface.

Volume-change is not visible finally in this case.

(B) The clay (each sample is like those used in the former observation) absorbs liquid water (19°C. in temperature) relatively very quickly and becomes

Table 9. Comparison of the Above (A) and (B) Observations.

(A) Observation (clay and vapour)			(B) Observation (clay and water)		
Nos. of samples	Time at when "hydrat." stop	"Hydrous Ratio".	Nos. of samples	Time at when hydrat. stop	Hydrous Ratio.
No. 1	38 hours	8.22%	No. 1'	6 hours	9.77%
No. 2	42	9.50	No. 2'	3	10.62
No. 3	40	6.76	No. 3'	4	10.56
No. 4	42	10.12	No. 4'	4	10.86
No. 6	43	7.63	No. 6'	4	7.92
No. 7	69	13.08	No. 7'	3	23.09
No. 8	66	11.64	No. 8'	3	22.29
No. 9	68	13.24	No. 9'	6	41.37
No. 10	64	12.82	No. 10'	5	41.84
No. 11	61	12.60	No. 11'	4	37.63

completely saturated until its hydrous ratio becomes constant and reaches the maximum limit. When the sample is not so compact as a shale or tuff, it deforms and changes its volume apparently owing to oversaturation. Further adding water, then the clay may become fluid and takes no definite cast at last.

When the compressed dry clay absorbing liquid water, "hydro-expansion" is distinctly recognized by naked eyes.

Then, further investigation on "hydro-expansion" of clay will, therefore, be carried on in the light of the above results.

Samples of artificially compressed powdered clay and liquid water shall be treated in the next main experiments.

Any influence of aqueous vapour will be neglected in consideration on the "hydro-expansion" of clay.

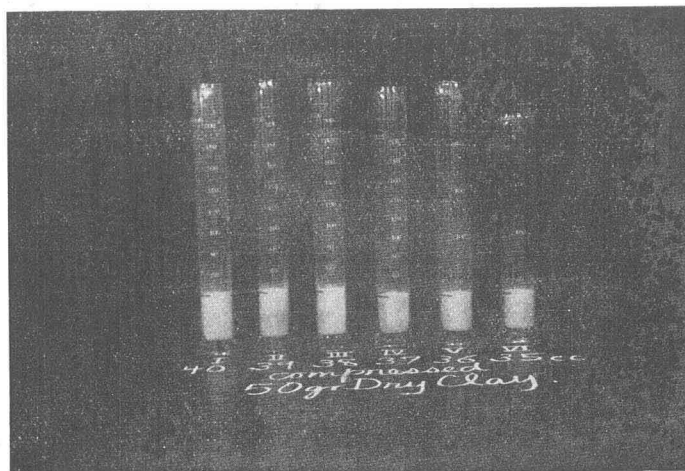
Chapter II. PRELIMINARY TEST ON HYDRAURIC VOLUME CHANGES OF SEVERAL INITIALLY COMPRESSED CLAY.

These tests are only some primitive simple examination, in which one can easily recognize the phenomenon "Hydro-expansion" of the clay, by the naked eye through the glass tubes.

(A) At first, 50 gr. each of powdered dry clay was taken in six mesh cylinders (No. I; No. II; No. III; No. IV; No. V and No. VI.) all of the apparent volumes of the clay were measured 40 cc.

The various compressions were applied to the clay in the mesh cylinders and each apparent volume reduced as follows: (see Pl. X)

No. I	(slightly compressed)	40 cc.
No. II		39 cc.
No. III		38 cc.
No. IV		37 cc.
No. V		36 cc.
No. VI	(most intensely compressed)	35 cc.



Pl. X. First dry powdered clay, 50 gr. each weight and compressed to 40 cc.-35 cc. in apparent volume.

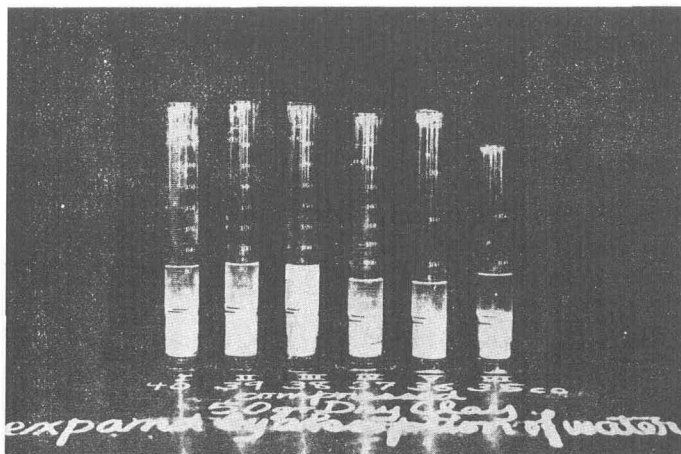
(B) Second, some quantity of water (19 temperature, which is common temperature in the tunnel) is gently poured into the mesh cylinders, and the clay allowed to absorb water thoroughly.

Now one can see exactly some volume changes of clay through the glass tubes, and these results were as follows :

No. I	40 cc. (in dry state) → 40.10 cc. (in wet state)
No. II	39 cc. (, , ,) → 40.15 cc. (, , ,)
No. III	38 cc. (, , ,) → 40.20 cc. (, , ,)
No. IV	37 cc. (, , ,) → 40.25 cc. (, , ,)
No. V	36 cc. (, , ,) → 40.30 cc. (, , ,)
No. VI	35 cc. (, , ,) → 40.40 cc. (, , ,)

Thus, the phenomenon, "Hydro-expansion" of clay was recognized and the larger change appeared in the stronger compressed samples. (see Pl. XI)

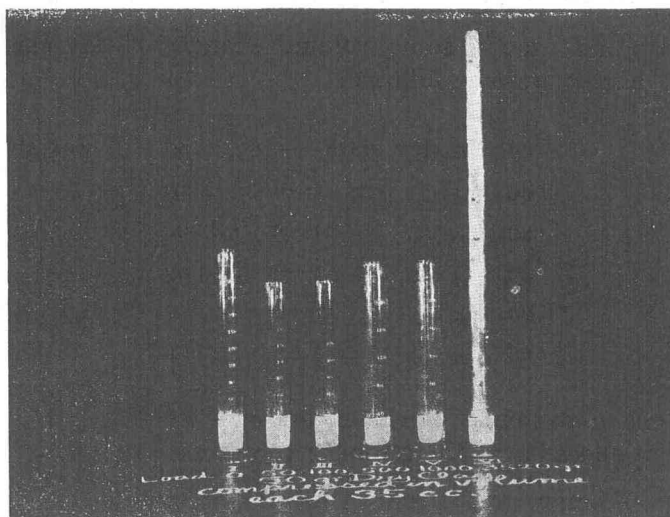
(A') The preliminary test described below was somewhat different from the former one. This time, all of the dry powdered clay (50 gr. in weight) was most intensely compressed in the mesh cylinders, until each apparent volume



Pl. XI. Samples of wet powdered clay, each changing apparent volume from the dry condition. Lower black lines on mesh cylinders show first surfaces in dry state and upper ones after the absorption of water into the clay powder.

become uniform (35 cc.) and then some several loads were put on the test materials (or dry clay) in the mesh cylinders, such as: (see Pl. XII)

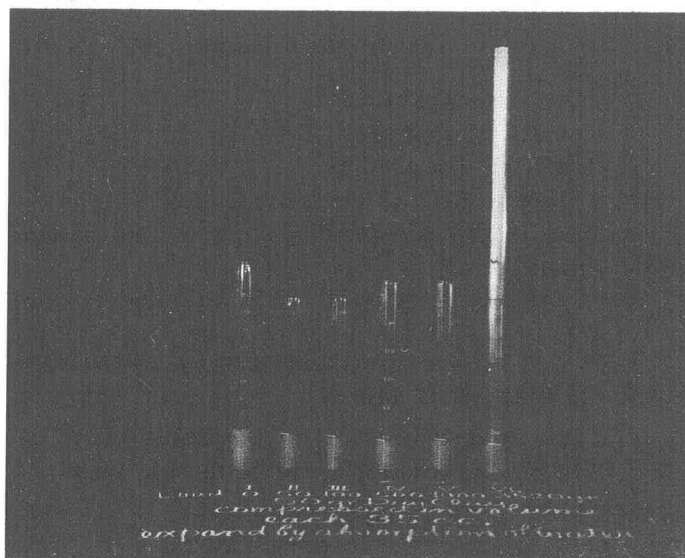
No. I'	.....	0 gr.	(no load)
No. II'	.....	50 gr.	load (lead shot)
No. III'	.....	100 gr.	load (lead shot)
No. IV'	.....	500 gr.	load (lead shot)
No. V'	.....	1000 gr.	load (lead shot)
No. VI'	.....	3520 gr.	load (gun-metal)



Pl. XII. Intensely compressed dry clay-powder 50 gr. each in weight and 35 cc. in volume upon which several load were put in the mesh cylinders.

(B') Some quantity of water (19° in temp.) was gently poured into the mesh cylinders, and the clay allowed to absorb water thoroughly. At this time, some several loads were put on each sample of test material in the mesh cylinder, except No. I', therefore, one can see somewhat different volume changes from the former test (B), such as: (see Pl. XIII).

No. I'		35 cc. (in dry state) → 40.41 cc. (in wet state)
No. II'		35 cc. (in dry state) → 38.25 cc. (in wet state)
No. III'		35 cc. (in dry state) → 37.82 cc. (in wet state)
No. IV'		35 cc. (in dry state) → 36.38 cc. (in wet state)
No. V'		35 cc. (in dry state) → 35.23 cc. (in wet state)
No. VI'		35 cc. (in dry state) → 35.00 cc. (in wet state)



Pl. XIII. Wet state of the intensely compressed clay, on which various loads were put.

CONCLUSION OF THIS CHAPTER.

(ON "HYDRO-EXPANSION" PRELIMINARY TESTS OF CLAY).

The above facts teach one that (1) some compressed clay changes its apparent volume when it absorbs water, and that its volume change is not the same, if compressive power is different. (2) Moreover, one can recognize the phenomenon "Hydro-expansion", in which some "expansive power" appears strongly enough that some load is pushed up in the mesh cylinder, but its power has a certain limit.

These preliminary tests give one some general idea on "Hydro-expansion" of clay which will be studied afterward (in Part III) in detail.

Part III. MAIN EXPERIMENTS.

Observations were made in detail of the phenomenon, "Hydro-expansion" of clay, and descriptions follow of such features as :

- (1) Relationship between E and C ;
- (2) Relationship between E and Q ;
- (3) Relationship between E and P ;
- (4) Relationship among E , P and S ;
- (5) Relationship among E , P and K ;
- (6) Relationship among E , C and Q ;
- (6) Relationship among E , P and C ;
- (6) Relationship among E , P and Q ;

where E = "Hydro-expansion"
 C = initial compression
 Q = quantity (in grams)
 P = pressure or load on test material
 S = size of dry powdered clay-grain (not particle but a small mass)
 K = kind of test material (as Tanna clay or Hanaoka clay etc.)

and H (= hydration) is always measured through these experiments, with reference to the relation between E and H .

Moreover, ϵ (= Hydro-expansive power) is observed, which is the most important subject and is the most noteworthy topic in this paper.

It will be found that E is always accompanied by "Hydro-expansion" and that it shows an enormous power in certain cases.

Chapter I. RELATIONSHIP BETWEEN E ("HYDRO-EXPANSION") AND C (INITIAL COMPRESSION GIVEN TO TEST MATERIAL).

It is known that the natural clay showing some strong "earth-pressure" in Tanna tunnel did not have uniform texture (porosity or compactness). Therefore, the pores among the particles of clay can be changed by any of several compressive powers within fairly wide limits. It is, however, unknown how strong compression existed or had been inflicted upon the clay-mass or clay-zone in the tunnel. But it may be possible artificially to duplicate the natural condition of some clay-texture.

Accordingly, a large number of test pieces of several different porosities were prepared for the experiments. The relationship was observed between

E ("Hydro-expansion") and C (initial compression on test pieces each of which held some compressed energy as "latent plasticity" in their bodies).

Test Material. K (kind of clay): perfectly dry powdered clay (specific gravity 2.65) taken in Tanna tunnel was used. S (size of clay-grains): under 0.01 cm.^3

Test Pieces. The above material was taken into a gun-metal cylindrical tube, of which the inside diameter, $2R$ was 2.7 cm. Q (the quantity of material) making each test piece was all the same, as $Q = 12.5 \text{ gr.}$ The powder in the cylindrical tube was compressed without any binding material by a 60 ton compression testing machine. The test pieces were made of equal cylindrical plate-formed clay-mass (their diameters $2R = 2.7 \text{ cm.}$, the same as that of the gun-metal tube). The thickness D of each test piece was different according to the several compressive powers C_n , such as $D_n = 2.4 \sim 0.8 \text{ cm.}$ It is necessary that the compression time be continued during one hour or more for each test piece. If not so long a time is used, the textures of the test pieces may not be uniform or it may impossible to make uniform standard test pieces, which show always certain regular results in any tests.

Testing Apparatus. "Hydro-expansion" of clay, Hukutomi's "Hydro-expansion" testing apparatus is used. Its construction can be seen in Fig. 5, in which a is a cylindrical tube made of gun-metal same as the one that was used formerly for making a test piece; b is a box made of brass-plate, in which the cylindrical tube is settled; c is a piston moving vertically in the cylindrical tube; d is a beam connected with the top of the piston on the one side to which

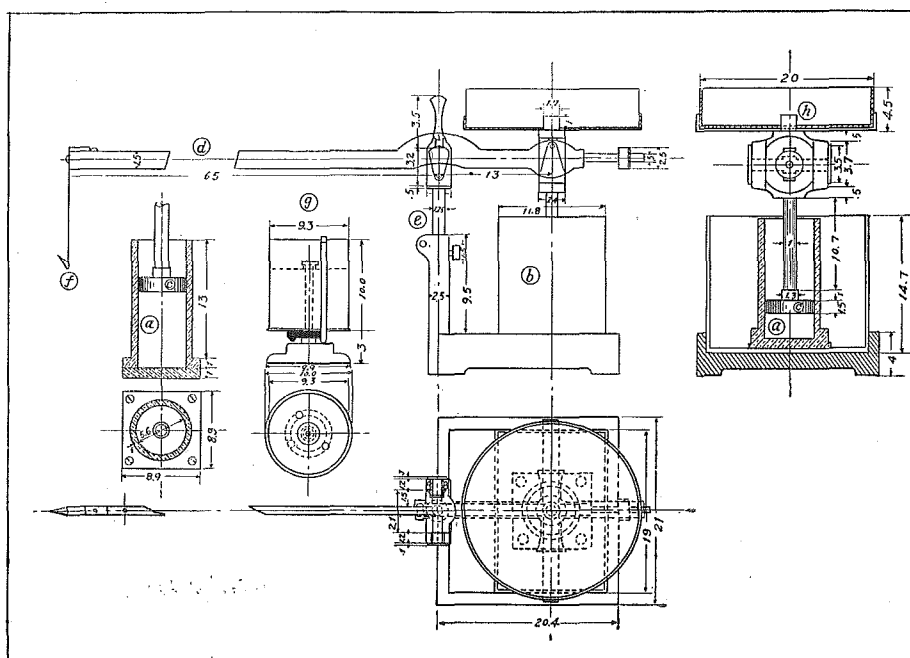
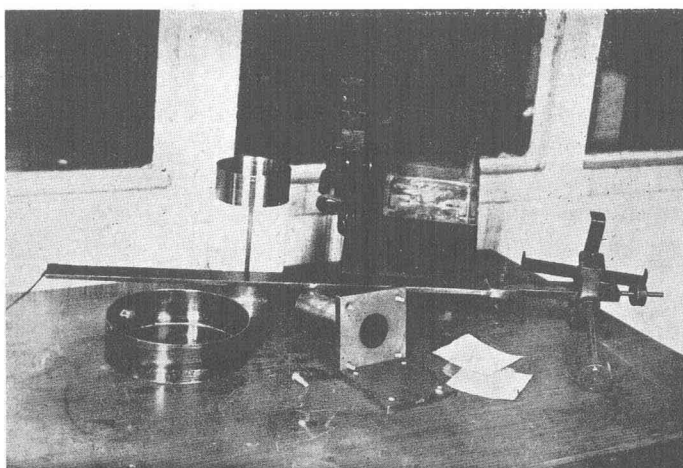


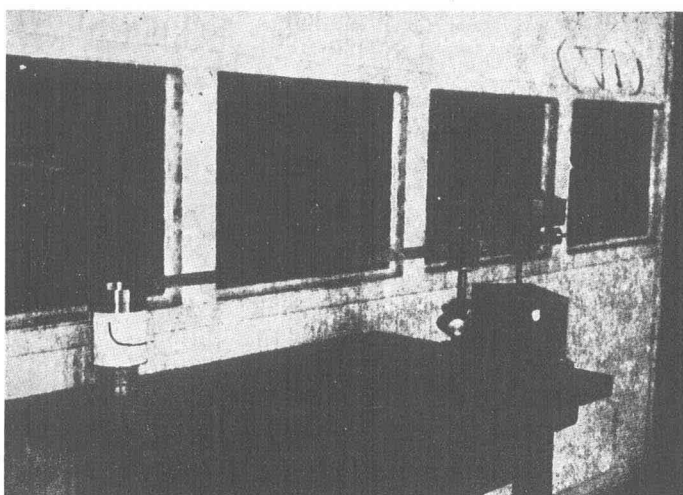
Fig. 5. Construction of "Hydro-expansion" testing apparatus.

is affixed a registering pen on the other side; *e* is a sharp wedge holding the beam at some point, not at the middle, but the length ratio of the piston side to the pen side=1:5, like a deformed chemical balance; *f* is a registering pen; *g* is a cylindrical registering clock-work drum; *h* is a dish or a scale fixed on the top of the piston to put some load on it.

A sheet of brass wire netting with two sheets filter paper is inserted under the base of the cylindrical tube to let some water soak into the inside of the tube through the net and paper. (see Pl. XIV and Pl. XV)



Pl. XIV. Several parts of the "Hydro-expansion" testing apparatus.



Pl. XV. An outer view of the "Hydro-expansion" testing apparatus.

For one experiment, 3 sets of like "Hydro-expansion" testing apparatus are always used in order to obtain a mean result or to gain as correct results as possible.

Beside that apparatus, a chemical balance; a registering thermometer and barometer; and a registering hygrometer etc. are prepared in the previously mention small special dark room, in which all of the conditions can be made like the conditions in any certain tunnel.

Testing Treatment. At first, a test piece is put in the cylindrical tube and the piston is brought completely into touch with the upper surface of the test piece. Then the beam is held horizontal with a regulator at the end of the beam, or balanced exactly. Next, a little quantity of pure water (19°C temperature) is poured into the box so as to give no hydrostatical pressure. Some water is allowed to sink through the brass net and two sheets of filter paper under the base of the cylindrical tube, which is affixed by 4 nut to a thick gun-metal plate. (see Fig. 6)

And then, if "Hydro-expansion" of clay appears, the thickness of the test piece becomes gradually larger and larger until it may reach to its maximum thickness, which we will be indicated on a sheet of the registering paper tied round the drum. The record will always show a time-relation and 5 times the real thickness change. An example of the recorded curve on the registering paper (see Fig. 7) shows that the phenomenon, "Hydro-expansion," had finished after 5.20 hours, or the thickness change of the test piece reached its maximum within that time, and the maximum thickness d was recorded as: $d = 1.04/5 \text{ cm}$.

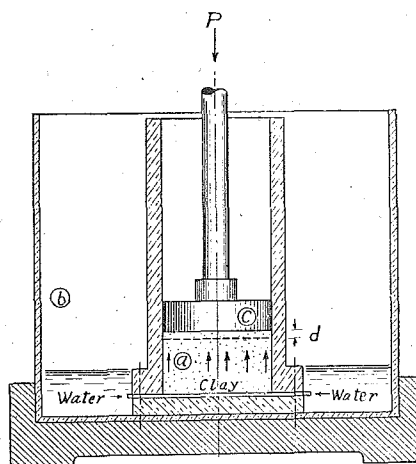


Fig. 6. Vertical section of the main part of the "Hydro-expansion" testing apparatus. a is a test piece placed in the cylindrical tube. b is the brass box. c is a piston put on the test piece.

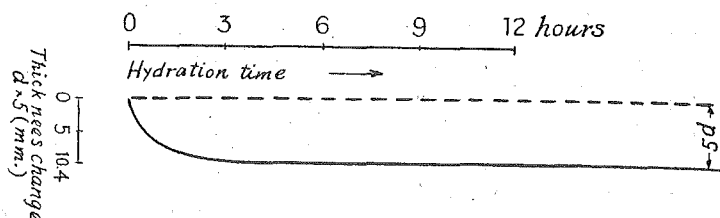


Fig. 7. An example of the recorded curve on the registering paper.

The phenomenon, "Hydro-expansion" of clay in a tunnel, appears, in usual case, on one inner cutting side within a clay-zone or massive body. Therefore, one can see only the natural thickness change in a tunnel. Thus, it is very convenient and satisfactory to know the thickness change of any test pieces through all of these experiments. But care must be taken against the occurrence of some boundary effect between the inner side of the cylindrical tube and

outer side of a test piece. Therefore, the inner surface of the cylindrical tube is polished as smooth as a surface of glass. Then one will know afterward that the boundary effect can be neglected for some enormous "expansive power," if a test piece is intensely compressed initially.

Test Results. In this experiment (Chapter I), all of the test pieces had the following values :

- K (kind of test material) = clay in the Tanna tunnel ; = K_1
 S (size of clay-grains) = under $0.01 \text{ cm.}^3 = S_1$
 Q (quantity of dry clay) = $12.5 \text{ gr.} = Q_1$
 $2R$ (diameter of test piece) = $2.7 \text{ cm.} = 2R_1$

But some differences were found their thicknesses or in volumes of the dry test pieces, and in their hydrations and in volume changes during absorbing water, according to the several initial compressive powers exerted upon the test pieces. (see Table 10)

Table 10. A table showing the relationship between C and E .

Nos.	C ton	C' kg/cm. ²	(γ)			(β)		(α)	
			D cm.	V cc.	v %	H gr.	h %	d cm.	e %
I	0.000	0.000	2.40	13.752	0.00	6.50	52.00	-0.483	-20.13
II	0.003	0.524	2.10	12.033	12.50	6.28	50.24	-0.100	- 4.76
III	0.005	0.873	2.00	11.460	16.67	6.03	48.24	-0.070	- 3.50
IV	0.010	1.745	1.90	10.887	20.82	6.02	48.16	-0.018	- 0.95
V	0.050	8.730	1.60	9.168	33.33	4.75	38.00	0.013	0.81
VI	0.125	21.820	1.15	6.590	52.08	3.37	26.96	0.215	18.70
VII	0.500	87.260	1.06	6.074	55.38	3.35	26.80	0.258	24.20
VIII	1.000	174.520	1.01	5.787	57.92	3.31	26.50	0.269	26.63
IX	2.000	349.040	1.00	5.730	58.33	3.25	26.00	0.272	27.20
X	3.000	523.560	1.00	5.730	58.33	3.19	25.50	0.275	27.50
XI	5.000	872.600	1.00	5.730	58.33	3.06	25.50	0.275	27.50
XII	10.000	1745.200	0.95	5.444	60.41	2.78	22.24	0.276	29.05
XIII	17.000	2966.840	0.86	4.928	64.17	2.55	20.40	0.260	30.23
XIV	23.000	4013.960	0.80	4.584	66.66	2.40	19.20	0.255	31.88

(α) "Hydro-expansion", (β) Hydration ;

(γ) Volume change of test pieces in dry state according to the several initial compressions.

C = initial compression given to test piece ;

C' = initial compression per unit area ;

D = thickness of dry test piece ;

V = volume of dry test piece ;

v = percentage of volume change ;

H = Weight of absorbed water ;

h = percentage of weight change during hydration, "hydrous ratio";
 d = thickness change of test piece during hydration;
 e = percentage of volume change during hydration.

In Table 10, No. I is a cylindrical plate test piece given no initial compression or $C = 0$; its thickness in the dry state $D = 2.40$ cm.; its volume in the same state $V = 13.752$ cc.; the weight of hydrated water $H = 6.50$ gr.; the hydrous ratio or the weight percentage of the above $h = 52.00$ %; its thickness change during hydration $d = -0.483$ cm. (that is, the thickness of the wet test piece after absorbing water shows some contraction or settlement of the powdered clay and thickness in this case $D - d = 2.40 - 0.82 = 1.57$ cm.); therefore, "Hydro-expansion" ratios $e = -20.13$ % ($d \cdot 100/D$ or $-0.483 \times 100/2.40$).

From No. II to No. IV, the test pieces compressed under several weak initial stresses show some negative "Hydro-expansions."

From No. V to No. XIV, these are, however, compressed so intensely before hydration, that their "Hydro-expansions" always appear as positive. Among them, from No. VIII ($C = 1$ ton; $D = 1.01$ cm.; $h = 26.50$ %; $e = 26.63$ % to No. XIV ($C = 23$ tons; $D = 0.80$ cm.; $h = 19.20$ %; $e = 31.88$ %), it can be seen that their "Hydro-expansion" ratio e increases gradually and the hydration ratio h decreases gradually too.

Accordingly, the two curves, which represent e and h , are drawn like straight lines directing upward and downward symmetrically, within a certain limited condition, and the curve, which represents v , runs like a straight line parallel to that of "Hydro-expansion" ratio e (see Fig. 8).

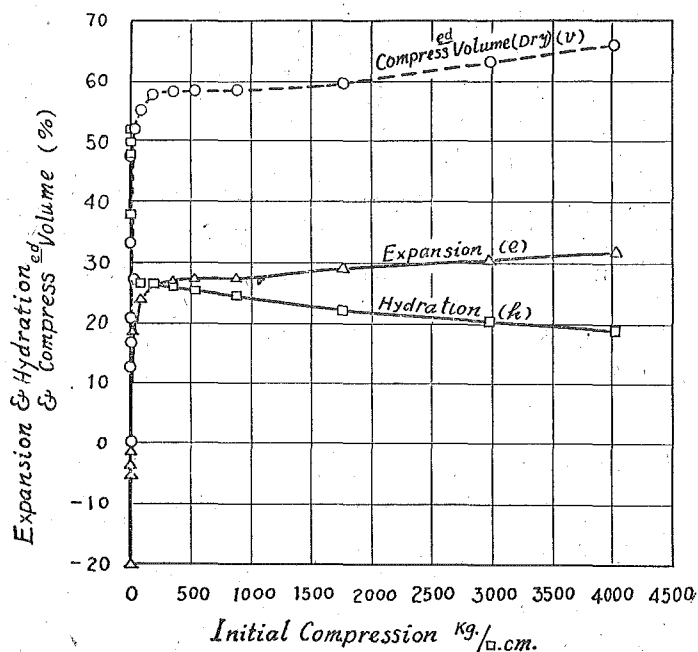


Fig. 8. Curves showing the relationships among e , h , v , and C .

It was already known that the phenomenon, "Hydro-expansion" of clay, appears when the clay has initially been strongly compressed, but one may presume that this phenomenon does not appear, if the initial compression has been so extremely strong as to eliminate any pores among the clay particles. In such a case, no or a little hydration is measured on some specimen like some old hard compact rock (as clay-slate etc.). Therefore, one can recognize that $h = 0$ and $e = 0$, if $C = \infty$.

These studies are, however, directed to an investigation of the phenomenon, "Hydro-expansion" of clay, within certain limited conditions like those in the Tanna tunnel. Thus, the above test results may satisfy the purpose. Some of these results will be examined again afterward in a later chapter in several ways.

SUMMARY OF THIS CHAPTER.

The experiments described teach at least the following facts.

(A) There are some definite relationships among E ("Hydro-expansion" of clay), H (hydration) and several C (initial compressions).

(B) Some loose clay may contract itself during hydration, that is, no or weak initial compression allows some clay to expand negatively by absorbing water. So that, some part of clay zone or mass in a tunnel can be loosed and made free from any positive "Hydro-expansion" by destroying its texture.

(C) If some "Hydro-expansion" of clay appears in a tunnel, it must have been already given a certain limited initial compression, not too weak nor too strong.

(D) Study of the relationships among e ("Hydro-expansion" ratio), h (its hydrous ratio) and C (initial compression) bring always certain definite identical results, if a definite quantity of some definite kind clay is treated in the same way.

(E) In these above experiments, "Hydro-expansion" of clay is expended freely, that is, if these exist no loads put on the test pieces, just as when no timbering works in a tunnel check the expansive power, the "Hydro-expansion" of clay pushes out the cutting surface within the clay zone or mass without any resistance, toward the inside of the tunnel.

Chapter II. RELATIONSHIP BETWEEN E ("HYDRO-EXPANSION") AND Q (QUANTITY OF TEST MATERIAL).

In this chapter, is reported some relationship between E and several Q under the same conditions, such as: K (kind of material) = clay taken in the Tanna tunnel; S (size of clay-grains) = under 0.01 cm^3 . and (initial compression) = 1 ton, or C' (initial compression per unit area of a test piece) = 83.68 kg/cm^2 .

Test Material. Material was all the same as that treated in the preceding chapter.

Test Pieces. In this case, several quantities of test material completely dry powdered clay were taken, such as:

$$Q_1 = 6.25 \text{ gr.}; Q_2 = 12.5 \text{ gr.}; Q_3 = 25 \text{ gr. or } Q_1 : Q_2 : Q_3 = 1 : 2 : 4.$$

The forms of test pieces were all the same as those treated in Chapter I, but their thicknesses and diameters of the cylindrical plate-formed test pieces were different from the former ones.

$$2R \text{ (diameter of the cylindrical plate)} = 3.9 \text{ cm.} = 2R_2$$

$$D \text{ (thickness of the test piece)} = 0.3 \text{ cm.}; 0.6 \text{ cm.}; 1.2 \text{ cm. or } D_1 : D_2 : D_3 = 1 : 2 : 4.$$

Testing Apparatus. The same as used in Chapter I, but the inner diameters of the cylindrical tubes of the "Hydro-expansion" testing apparatus were different from the former ones.

$$2R = 3.9 \text{ cm.} = 2R_2.$$

Testing Treatment. The same as the former treatment.

Test Results. Table 11 and Figure 9 show the results of the tests.

Three of each kind were tested and in this table there shown the mean value of the results.

Table 11. Results on relationships among Q , h and e .

Nos.	Q gr.	D cm.	(β)		(α)	
			H gr.	h %	d cm.	e %
XV	6.25	0.3	3.33	53.28	0.134	44.67
XVI	12.50	0.6	5.22	41.76	0.185	30.83
XVII	25.00	1.2	8.62	34.47	0.189	15.75

Q = quantity of test material in dry state;

D = thickness of test piece in dry state;

H = weight of absorbed water;

h = hydrous ratio;

d = thickness change of test piece during hydration;

e = percentage of volume change during hydration.

As is seen from the above table (*Table 11*), the test pieces No. XV, No. XVI and No. XVII are each such as:

$$Q_1 : Q_2 : Q_3 = 6.25 : 12.50 : 25.00 = 1 : 2 : 4,$$

$$D_1 : D_2 : D_3 = 0.3 : 0.6 : 1.2 = 1 : 2 : 4,$$

$$H_1 : H_2 : H_3 = 3.33 : 5.22 : 8.62 = 1 : 1.57 : 2.58,$$

$$h_1 : h_2 : h_3 = 53.28 : 41.76 : 34.47 = 1 : 0.78 : 0.65,$$

$$d_1 : d_2 : d_3 = 0.134 : 0.185 : 0.189 = 1 : 1.38 : 1.41,$$

$$e_1 : e_2 : e_3 = 44.67 : 30.83 : 15.75 = 1 : 0.67 : 0.35.$$

Thus, the relationships among Q or D , H , h , d and e are not always proportional, that is, H and d are not uniform, or h and e represent also no uniformity according to the quantities of clay material. Fig. 9 shows some of the above facts by two curve (e and h).

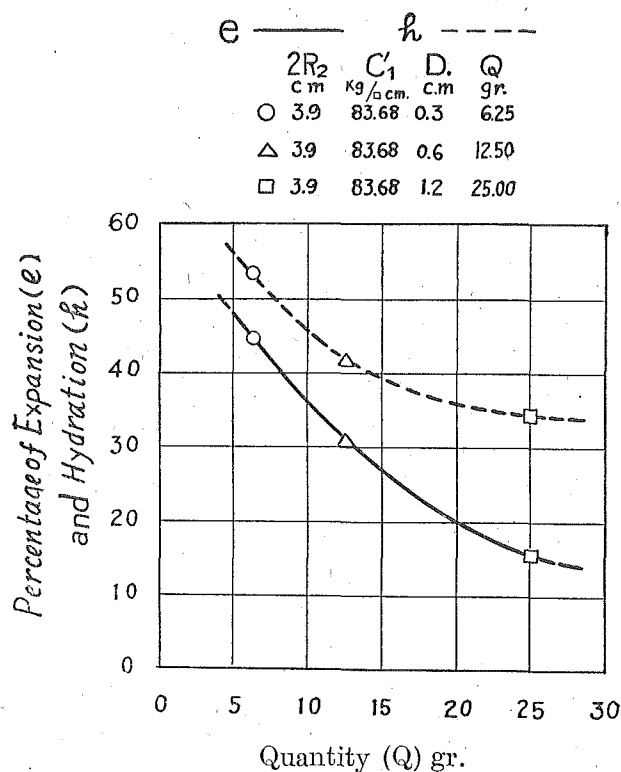


Fig. 9. Curves represent certain relationships among e , h and Q .

SUMMARY OF THIS CHAPTER.

From the results of the present that of "Hydro-expansion" of clay in the case when no load was applied on the test pieces during hydration, conclusions may be drawn as follows:

Clay of small grains under a certain limited size shows the phenomenon of "Hydro-expansion" when it is given a certain definite initial compression. The quantity of absorbed water does not increase at the rate of increase of the amount of test material but, on the contrary, the percentage of absorbed water decreases.

The increase of volume due to hydration shows a relation similar to the above and the percentage of volume change during hydration decreases with the amount of test material.

It is worthy of notice that the percentages of absorbed water and "Hydro-expansion" are greater in the smaller quantity of test material than in the greater one. This fact it to be taken into consideration when one wishes to apply this experimental result to a practical case where a large amount of clay usually exists.

Chapter III. RELATIONSHIP BETWEEN E ("HYDRO-EXPANSION") AND P (APPLIED COMPRESSION ON TEST PIECE DURING HYDRATION).

In the preceding two chapters, "Hydro-expansion" of clay was measured under no load on the test piece during hydration, that is, the volume-change due to hydration was permitted freely with no restriction.

In the present experiment all test pieces were compressed with a definite load during hydration. In this case, test pieces well pushing up the applied load immediately on beginning of absorption in spite of its considerable size and the phenomenon of "Hydro-expansion" appears.

In regard to the force to overcome the applied load P , the author suspected its existence at the same time when he found the phenomenon of "Hydro-expansion." He calls this force "Hydro-expansive power" or briefly "expansive power" recognizing its importance in his experiment. This force is denoted by " ϵ ".

Experimental results described in the present chapter will be often referred to in many other investigations which will be described hereafter. "Hydro-expansive power" ϵ is measured by the changing of volume of absorbent material caused by hydration. Moreover by applying load on material during hydration, the strength of the expansive power may be known. When the initial compression which is applied to test pieces at the beginning of test is weak and the structure of the material does not become dense, test pieces shrink after hydration even in the case of no load. In this case the expansive force can not taken be into consideration. There is also a special case in which test pieces do not expand and do not shrink. The increase in bulk means the existence of internal stress ϵ and material does not increase in bulk without the existence of ϵ . Therefore, for the investigation of ϵ experiments are to be carried out with the test pieces which easily show "Hydro-expansion".

Among the materials which were used in the former tests, material of K_1 and S_1 having the initial compression of $C_1 = 1$ ton or $C_2 = 2$ tons or $C_3 = 3$ tons are found to be most fit for the author's present testing plant. With regard to the quantity of materials, choice was made of $Q_1 = 6.25$ gr., $Q_2 = 12.5$ gr. and $Q_3 = 35$ gr., which were used in the preceding test, for the purpose of referring to the results in that test.

Thus, test pieces used in the present experiment were expected to show an obvious "Hydro-expansion". However, it will be supposed that "Hydro-expansion" under a certain load P will not be like that under no load and under a load over a certain definite limit it may be restrained and not appear. In such case, this certain definite load is to be equal to the expansive power ϵ on that occasion or greater than it. Then in the case of $\epsilon > P$ "Hydro-expansion" E can occur and in the case of $\epsilon < P$ it can not.

When a strong earth pressure caused by "Hydro-expansion" is observed on inner cutting sides of tunnel or adit within an absorbent clay zone as in the Tanna tunnel and Hanaoka adit, timbering which is to protect the tunnel or adit from this earth pressure is to be designed so that the expansive power ϵ is equal to the resisting power of timbering or, if possible, smaller than it. The author does not consider that the practical design of timbering in tunnel or adit within an absorbent clay zone becomes possible by his investigation but he believes that this present experiment must conduce to the completion of the investigation about expansive power.

Test Material. Material was K_1 and S_1 such as that treated in the preceding two tests, namely it was perfectly dry powdered clay taken in Tanna tunnel having the grain size of under 0.01 cm^3 .

Test Pieces. Test pieces were all the same as those of No. XVI treated in the preceding chapter and had the following quantity, dimension and initial compression:

$$\begin{aligned} Q_2 &= 12.5 \text{ gr.}; \\ C_1 &= 1 \text{ ton or } C_1 = 83.68 \text{ kg/cm.}^2; \\ 2R_2 &= 3.9 \text{ cm.}; \\ D_2 &= 0.6 \text{ cm.} \end{aligned}$$

Several tens of test pieces were made.

Testing Apparatus. Testing apparatus was the same as that used in the preceding test, but it was so made that any load P could be applied to the test piece during hydration. As a load, shots were used. Three sets of equal "Hydro-expansion" testing apparatuses having the cylindrical tube whose inner diameter was 3.9 cm. were used as in the preceding test.

Testing Treatment. The same as the former treatment excepting the compression of test pieces during hydration.

Test Results. Tables 12 shows the results. In this table there are shown the mean values of three results which were obtained from three sets of like testing apparatuses.

Table 12. A table of the results on the relationship among e , h and P .

Nos.	P kg/11.95 cm. ²	P' kg/cm. ²	(β)		(α)	
			H gr.	h %	d cm.	e %
XVI ₁	0	0	5.22	41.76	0.185	30.83
XVI ₂	1	0.084	4.63	37.00	0.109	18.17
XVI ₃	2	0.167	4.20	33.60	0.064	10.67
XVI ₄	3	0.251	3.90	31.20	0.040	6.67
XVI ₅	5	0.418	3.80	30.40	0.028	4.67
XVI ₆	7	0.586	3.68	29.44	0.014	2.33
XVI ₇	10	0.837	3.55	23.40	0.010	1.67
XVI ₈	13	1.088	3.43	27.44	0.002	0.38
XVI ₉	15	1.255	3.33	26.64	0	0

P = Applied compression on circular area of 11.95 cm.² of test piece during hydration;

P' = Applied compression per unit area;

H = weight of absorbed water;

h = hydrous ratio;

d = thickness change of the test piece during hydration;

e = percentage of volume change during hydration.

As already mentioned above, test pieces of Nos. XVI₁ to XVI₉ are all the same as those of No. XVI used in the preceding test and moreover the test pieces of No. XVI₁ are for the case of $P=0$ like those of No. XVI. Therefore, the experimental results obtained from the individual test pieces of No. XVI are brought into Table 12 as those of No. XVI₁.

No. XVI₂ is for the case of $P=1$ kg or $P'=0.084$ kg/cm.², that is, values of the tested results for No. XVI₁ are those which were measured applying the compression of 1 kg. on the test pieces during hydration.

In the former case of $P=0$, the thickness change of test pieces during hydration " d " is 0.185 cm., while in the case of $P=1$ kg. it becomes 0.109 cm. Comparing the two cases the percentage of the volume change during hydration " e " decreases from 30.83% to 18.17%. Regarding absorbed water " H ", it decreases from 5.22 gr. to 4.63 gr. and consequently the hydrous ratio " h " decreases from 41.76% to 37.00%.

In a similar manner, for other experimental results concerned with Nos. XVI₃ to XVI₈ which are for the case of $P=2$ kg., $P=3$ kg., $P=5$ kg., $P=7$ kg., $P=10$ kg. and $P=13$ kg. respectively, it is observed that d and e decrease at a certain rate with the increase of P and at last they reach zero at just $P=15$ kg. or $P'=1.255$ kg/cm.². At $P=15$ kg. absorbed water " H " is 3.33 gr. and hydrous ratio " h " becomes 26.64%. In Fig. 10 the relationships among e , h and P' are graphed.

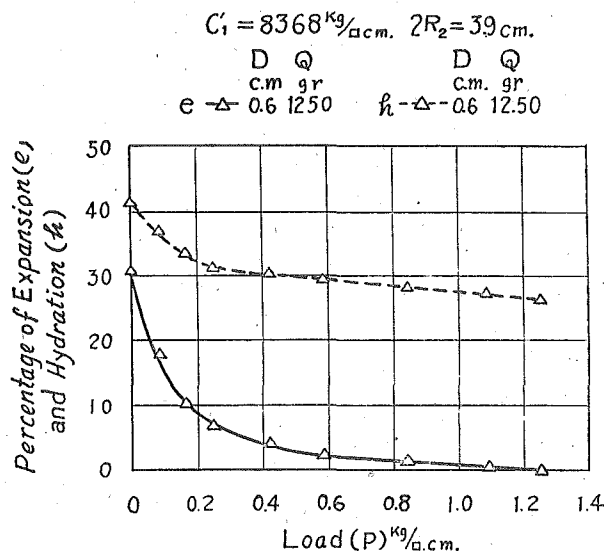


Fig. 10. Curves representing certain relationships among e , h and P .

SUMMARY OF THIS CHAPTER.

The conclusions to be drawn from the results of the present test may be summarized as follows:

I. Absorbent materials, such a clay, exhibit the phenomenon of "Hydro-expansion" E by absorbing water. However, when a test piece is compressed with a load P during hydration, the "Hydro-expansion" decreases at a certain rate with the increase of this compressing load P and when this compressing load P reaches to a certain definite amount, the "Hydro-expansion" ceases to appear. Therefore, the "Hydro-expansion" E can be completely restrained by means of a certain definite amount of load. Consequently the present experimental result offers proof that "Hydro-expansive power" appearing in the actual cases, such as tunnel and adit, may be completely restrained by an artificially applied load. The experimental results shows also the possibility of the measurement of "Hydro-expansive power" ϵ .

But these experimental were made under the definite conditions of initial compression C_1 , quantity of material Q , size of grain S and kind of material K . Therefore, as to the correlation of these many conditions much further investigation is necessary for predicting the more general behavior of absorbent materials in nature.

II. Concerning the absorbend water, the present test brought somewhat interesting results into view. The percentage of absorbing water " h " decreases with the increases of the applying load P and the curve showing the relation between P and h is similar to that of P and e . These two curves seem to run parallel with each other. But, H never reaches zero, in spite of the fact that

the applied load increases to a certain definite amount and the "Hydro-expansion" ceases to appear. Therefore, these two curves never intersect or coincide at their ends.

Even a natural hard rock absorbs water. Therefore, it is no wonder that it is impossible to make $h = 0$ for a clay.

From the results obtained in Tests I and III, it can be concluded that absorbent materials do not always expand by hydration. Some loose clay contracts itself during hydration when it is not so strongly initially compressed. Even the hard compact clay compressed at the beginning of test does not expand by hydration when it is compressed during hydration by a load over a certain definite amount.

In other word, even in a case in which drainage is impossible the "Hydro-expansion" can be restrained by loosening the structure of a clay and permitting free absorption or by compressing a clay strongly over a certain definite degree and preventing free absorption.

Chapter IV. RELATIONSHIP BETWEEN E ("HYDRO-EXPANSION") AND S (POWDER-BLOCK SIZE OF TEST MATERIAL).

In this chapter, "powder-block size" S has the same meaning as "size of powdered test material", "size of dry powdered grain" or "powdered grain passing through a certain sieve". S means not only the size of particle but also a small powder-block. The author determined the powder-block size " S " with sieves.

An important fact to remember in all soil testing in the variability of powder-block size in material. Therefore, in this test the present author investigated the influence of the powder-block size " S " upon the "Hydro-expansion" " E " to gain more detailed information and thereby to make his laboratory experiment more applicable to securing quite satisfactory estimates of natural "Hydro-expansion" characteristics in tunnel and adit.

Test Material. Following three powder-block sizes were used:

$$\begin{aligned} S_1 &= \text{under } 0.01 \text{ cm.}^3, \\ S_2 &= 0.025 \quad 0.05 \text{ cm.}^3, \\ S_3 &= 0.1 \text{ cm. } 0.2 \text{ cm.}^3. \end{aligned}$$

This material was perfectly dry powdered clay taken in Tanna tunnel as denoted by K_1 in the former tests.

Test Pieces. Test pieces were all made to a cylindrical plate-form having the quantity of $Q_2 = 12.5$ gr., diameter of $2R_2 = 3.9$ cm. and thickness of $D = 0.6$ cm. As initial compression all these test pieces were compressed with a load of $C_1 = 1$ ton. or $C' = 83.68$ kg/cm.². All the testing conditions were the same as in the preceding test excepting the powder-block size.

Testing Apparatus. Same as in the preceding test.

Testing Treatment. Same as in the preceding test, too.

Testing Results. For the material of the powder-block size under 0.01 cm.^3 , results had been already obtained in the preceding test.

Therefore, in this test, only two kinds of test pieces having respectively two different powder-block sizes of S_2 and S_3 were tested.

In Table 13, are shown the obtained results.

Table 13. Results on relationships among P , e and h for three different "Powder-Block Sizes" S .

Nos.	P kg/11.95 cm. ²	P' kg/cm. ²	(β)		(α)	
			H gr.	$h\%$	d cm.	$e\%$
XVI ₁	0	0	5.22	41.76	0.185	30.83
XVI' ₁	0	0	3.92	31.33	0.096	15.94
XVI'' ₁	0	0	3.03	24.20	0.058	9.58
XVI ₂	1	0.084	4.63	37.00	0.109	18.17
XVI' ₂	1	0.084	3.44	27.52	0.041	6.75
XVI'' ₂	1	0.084	2.92	23.30	0.028	4.72
XVI ₄	3	0.251	3.90	31.20	0.040	6.67
XVI' ₄	3	0.251	3.27	26.13	0.031	5.11
XVI'' ₄	3	0.251	2.83	22.60	0.018	3.00
XVI ₆	7	0.586	3.68	29.44	0.014	2.33
XVI' ₆	7	0.586	3.15	25.20	0.014	2.33
XVI'' ₆	7	0.586	2.68	21.47	0.014	2.33
XVI ₈	13	1.088	3.43	27.44	0.0023	0.38
XVI' ₈	13	1.088	2.92	23.33	0.0120	2.00
XVI'' ₈	13	1.088	2.52	20.13	0.0130	2.17
XVI ₉	15	1.255	3.33	26.64	0	0
XVI' ₉	....	....	....	....	....	....
XVI'' ₉	....	....	....	....	....	....
XVI ₁₀	....	....	....	....	....	....
XVI' ₁₀	20	1.674	2.75	22.00	0.008	1.33
XVI'' ₁₀	20	1.674	2.45	19.60	0.010	1.67
XVI ₁₁	....	....	....	....	....	....
XVI' ₁₁	24	2.003	2.73	21.84	0.004	0.67
XVI'' ₁₁	....	....	....	....	....	....

Table 00.—Continued.

Nos.	P kg/11.95 cm ² .	P' kg/cm ² .	(β)		(α)	
			H gr.	$h\%$	d cm.	$e\%$
XVI ₁₂	....	....	....	....	....	....
XVI' ₁₂	27	2.259	2.70	21.60	0	0
XVI'' ₁₂	27	2.259	2.40	19.20	0.006	1.00
XVI ₁₃	....	....	....	....	....	....
XVI' ₁₃	....	....	....	....	....	....
XVI'' ₁₃	30	2.594	2.37	18.96	0.002	0.33
XVI ₁₄	....	....	....	....	....	....
XVI' ₁₄	....	....	....	....	....	....
XVI'' ₁₄	34	2.845	2.35	18.80	0	0

P = applied compression on circular area of 11.95 cm². of test piece during hydration;

P' = applied compression per unit area;

H = weight of absorbed water;

h = hydrous ratio;

d = thickness change of test piece during hydration;

e = percentage of volume change during hydration;

Nos. XVI₁ to XVI₁₄; S_1 = under 0.01 cm³.;

Nos. XVI'₁ to XVI'₁₄; S_2 = 0.025~0.05 cm³.;

Nos. XVI''₁ to XVI''₁₄; S_3 = 0.10~0.20 cm³.;

Fig. 11 shows the relationship among percentage of expansion " e ", hydrous ratio " h " and applied compression during hydration " P ", for the test pieces having the different powder-block sizes.

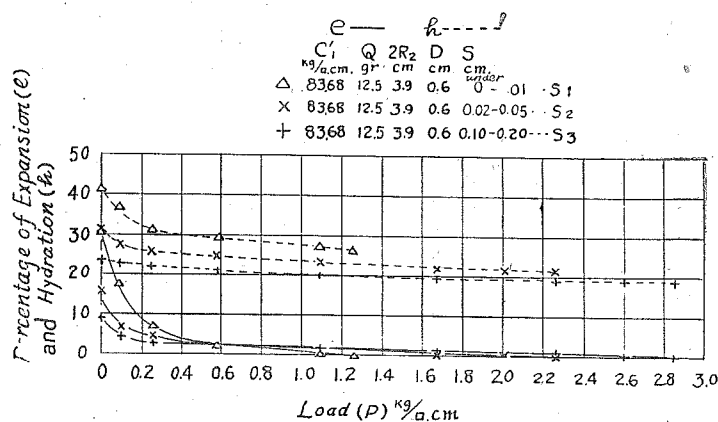


Fig. 11. Curves representing certain relationships among e , h and P' for three different "Powder-Block Sizes".

Both the table and figure show the different results for test pieces having the different powder-block sizes in spite of the fact that the tests were made under like conditions and with the same test pieces excepting the difference in powder-block size.

For example, in three different cases of S_1 , S_2 , phenomenon of "Hydro-expansion" "E" ceases to appear when a load applied during hydration reaches 1.255 kg/cm²., 2.259 kg/cm². and 2.845 kg/cm². respectively and therefore in the absorbent material having the greater powder-block size greater "Hydro-expansive power" "ε" appears.

For another example, when a test piece absorbs water under no load the volume change due to hydration becomes smaller with the increases in the powder-block size.

Applying the above two facts obtained from the laboratory experiment to the actual cases such as tunnel and adit, it is suggested that in the place consisting of absorbent material with large powder-block size, "Hydro-expansive power" is felt severely, but on the contrary the quantity of pushed out soils is small. In short, when powder-block size is great, expansive power is also great but quantity of pushed out soil is not.

Therefore, when one wishes to restrain the "Hydro-expansion" of clay, the powder-block size is to be taken into consideration.

Furthermore, the curves in Fig. 11 furnish other facts than the above mentioned ones which will be considered later on.

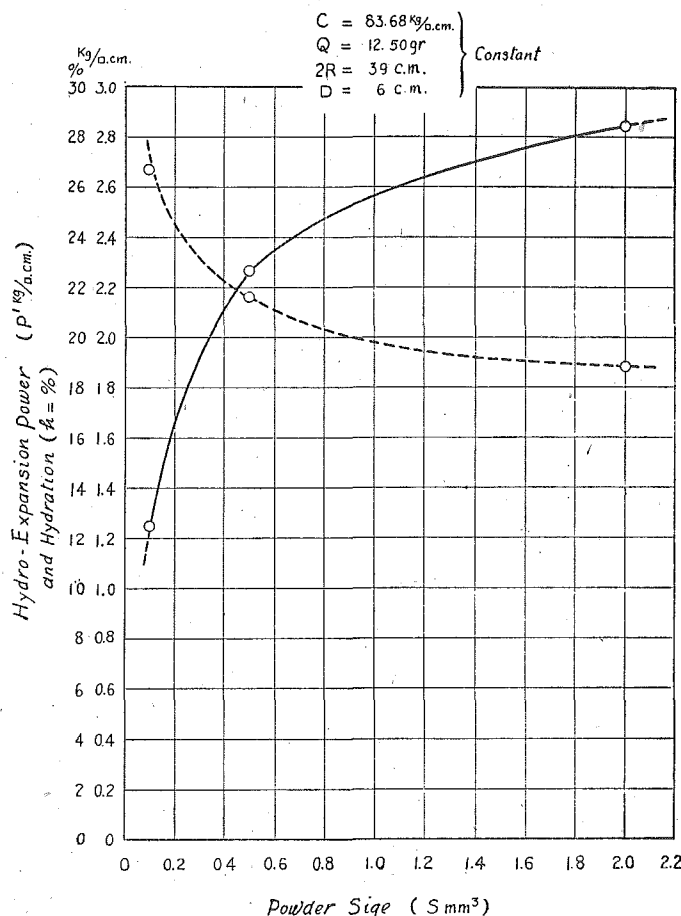
Next, the hardness of the powder-block of clay and the density of its structure exert a large effect to the hydration and "Hydro-expansion". All of the powder-blocks of clay used in the present test could be considered to have equal hardness and structure, and therefore as to this point no attention was needful. But, water must be concerned in the hardness of the powder-block of clay and therefore, clay was as completely drained and dried as possible, so that it might not degenerate, of course.

As already mentioned above, the phenomenon of "Hydro-expansion" is effected by the difference in powder-block size of absorbent material and thereby "Hydro-expansive power" is different according to powder-block size as follows:

Three kinds of materials having the powder-block sizes $S_1 = \text{under } 0.01 \text{ cm}^3$., $S_2 = 0.025 \sim 0.05 \text{ cm}^3$. and $S_3 = 0.10 \sim 0.20 \text{ cm}^3$. can not expand under load of $P' = 1.255 \text{ kg/cm}^2$., $P' = 2.259 \text{ kg/cm}^2$. and 2.845 kg/cm^2 . respectively.

In Fig. 11' the relationship between the powder-block size of clay "S" and "Hydro-expansive power" "ε" is shown with a full line.

In the same figure, the relationship between the powder-block size of clay "S" and the percentage of absorbed water "h" under equal to the expansive power is plotted with a broken line.

Fig. 11'. Curves representing relationsphs among P' , h and S .

Chapter V. RELATIONSHIP BETWEEN E ("HYDRO-EXPANSION") AND K (KIND OF TEST MATERIAL).

Test materials used in main Tests I to IV were all K_1 , that is, dry powdered clay taken in Tanna tunnel. But, in the present test other kinds of material taken in other places were used for further researching the property of "Hydro-expansion". The materials used in this test were as follows:

- K_2 = residual clay taken in Hanaoka mining gallery in Akita Prefecture,
- K_3 = tufaceous shale from open cut at Fushun Coal Mine in Manchuria.

The former, K_2 , is residual clay metamorphosed from the country rock (tertiary tuff) in the black ore deposit. When the clay zone in that place is excavated, water is absorbed and then the so-called "earth pressure" appears seriously destroying the timbering works just as in Tunna tunnel. Therefore in Hanaoka Mine adits, there were some which had to be abandoned. However, by trial keeping that clay zone in a dry state with a good ventilation, it

hardened and "earth pressure" immediately decreased. This fact shows the notable relation between the hydration and "earth pressure" in an actual case.

The latter, K_3 , is a shale spread over the oil shale which covers conformably the Fushun coal seam and it becomes very tufaceous. It comprises a part of the thick seam known as "green shale"¹⁾.

Absorbing water, it immediately changes to clayey material and decreases the angle of repose allowing the equilibrium of the clay mass to break down. And then it often begins to slip into the bottom of the open cut greatly interrupting the coal-mining business there.

This rock absorbs water by itself in the field and thereby it shows obviously the volume change. Therefore, this rock is one of samples which shows a fact that "Hydro-expansion" must be concerned in the occurrence of a land-slip.

Karl Terzaghi²⁾ concluded as follow in his papers:

"Swelling of clay is nothing more or less than the purely elastic expansion produced by the elimination of the surface tension of the capillary water. Therefore, local evaporation of the capillary water or local flooding of the surface of clay deposits produces secondary stresses whose intensity is far greater than the weight of the heaviest structures and which were found to be the primary cause of many vast soil displacements, known as land-slips".

Even if his statement is assumed to be not assented to as it stands, there is no denying the fact that it serves as a good reference to the investigations of "Hydro-expansion" and initial motive power of land-slips.

Author will now describe his experimental conditions and results.

Test Material. The above mentioned materials, K_1 , K_2 and K_3 were used and their powder-blocks were all sifted to a size of under 0.01 cm^3 . i.e. S_1 .

Test Pieces. Same as those used in Test III, viz.,

$$C_1' = 83.68 \text{ kg/cm}^2.,$$

$$Q_2' = 12.5 \text{ gr.},$$

$$2R_2 = 3.9 \text{ cm.},$$

$$D_2 = 0.6 \text{ cm.}$$

Testing Apparatus. Same as used in Test III.

Testing Treatment. Same as used in Test III.

Test Results. The results of the tests are shown in Table 14 and the diagrammatic relations between h and P' and between e and P' becomes as shown in Fig. 12.

1) K. Uwatoko, the Oil Shale Deposit of Fushun, Manchuria, p. 123.

2) Karl Terzaghi, Erdbaumechanik auf bodenphysikalischer Grundlage, 1925. Old earth-pressure Theories and new Test results, Engineering News-Record, 1920. Principles of soil mechanics, Engineering News-Record, 1925.

Table 14. Relationships Among, P , e and h for three different Materials K_1 , K_2 and K_3 .

Nos.	P kg/11.95 cm ² .	P' kg/cm ² .	β		α	
			H gr.	h %	d cm.	e %
XVI ₁	0	0	5.22	41.76	0.185	30.83
XVI''' ₁	0	0	7.59	60.72	0.310	51.67
XVI'''' ₁	0	0	5.00	40.00	0.140	23.33
XVI ₂	1	0.84	4.63	37.00	0.109	18.17
XVI'' ₂	1	0.84	6.30	50.40	0.135	22.50
XVI''' ₂	1	0.84	4.25	34.00	0.066	11.00
XVI ₄	3	0.251	3.90	31.20	0.040	6.67
XVI''' ₄	3	0.251	5.90	47.20	0.088	14.67
XVI'''' ₄	3	0.251	3.75	30.00	0.025	4.17
XVI ₅	5	0.413	....	....	....	....
XVI''' ₅	5	0.418	....	....	....	....
XVI'''' ₅	5	0.418	3.57	28.53	0.012	1.95
XVI ₅₋₆	6	0.502	....	....	....	....
XVI''' ₅₋₆	6	0.502	5.73	45.84	0.055	9.17
XVI'''' ₅₋₆	6	0.502	3.48	27.84	0.004	0.67
XVI ₆	7	0.586	3.68	29.44	0.014	2.33
XVI''' ₆	7	....	....	....	....	....
XVI'''' ₆	7	0.586	3.45	27.60	0	0
XVI ₇	10	0.837	3.55	28.40	0.010	1.67
XVI''' ₇	10	0.837	3.55	44.40	0.044	6.0
XVI'''' ₇	10	0.837	....	....	....	....
XVI ₈	13	1.088	3.43	27.44	0.002	0.38
XVI''' ₈	13	1.088	....	....	....	....
XVI'''' ₈	13	1.088	....	....	....	....
XVI ₉	15	1.255	3.33	26.64	0	0
XVI''' ₉	15	1.255	5.30	42.40	0.030	5.00
XVI'''' ₉	15	1.255	....	....	....	....
XVI ₁₀	20	1.674	....	....	....	....
XVI''' ₁₀	20	1.674	5.00	40.00	0.023	3.72
XVI'''' ₁₀	20	1.674	....	....	....	....

Table 14.—*Continued.*

Nos.	P kg/11.95 cm.	P' kg/cm ²	β		α	
			H gr.	h %	d mm.	e %
XVI ₁₁₋₁₂	25	2.094	....	....	....	....
XVI''' ₁₁₋₁₂	25	2.094	4.85	28.80	0.015	2.50
XVI'''' ₁₁₋₁₂	25	2.094	....	....	....	....
XVI ₁₃	30	2.510	....	....	....	....
XVI''' ₁₃	30	2.510	4.70	37.60	0.010	1.67
XVI'''' ₁₃	30	2.510	....	....	....	....
XVI ₁₅	35	2.929	....	....	....	....
XVI''' ₁₅	35	2.929	4.65	37.20	0.008	1.33
XVI'''' ₁₅	35	2.929	....	....	....	....
XVI ₁₆	38	3.180	....	....	....	....
XVI''' ₁₆	38	3.180	4.63	37.04	0.005	0.83
XVI'''' ₁₆	38	3.180	....	....	....	....
XVI ₁₅₋₁₇	40	3.347	....	....	....	....
XVI''' ₁₅₋₁₇	40	3.347	4.60	36.80	0	0
XVI'''' ₁₅₋₁₇	40	3.347	....	....	....	....

P = applied compression on circular area of 11.95 cm². of cylindrical plate formed test piece;

P' = applied compression per unit area;

H = weight of absorbed water;

h = hydrous ratio;

d = thickness change of test piece during hydration;

e = percentage of thickness change;

Nos. XVI₁ to XVI₁₇ = test pieces of material K_1 ;

Nos. XVI₁''' to XVI₁₇''' = test pieces of material K_2 ;

Nos. XVI₁'''' to XVI₁₇'''' = test pieces of material K_3 ;

Tested results about are quoted from Test III. Regarding K_2 and K_3 they were tested under quite the same conditions as K_1 . The results bear a close resemblance to each other as shown in Fig. 12. When a test piece is compressed with a load P during hydration, the percentages of both absorbed water " h " and of "Hydro-expansion" " e " decrease with logarithmic curves with the increase of load P applied during hydration. When this load P attains to a certain definite amount, though the test piece keeps on absorbing water, the volume change due to hydration ceases to appear and under the load over a certain limit "Hydro-expansion" becomes impossible.

Two curves of h and e seem to run parallel with each other. Comparing

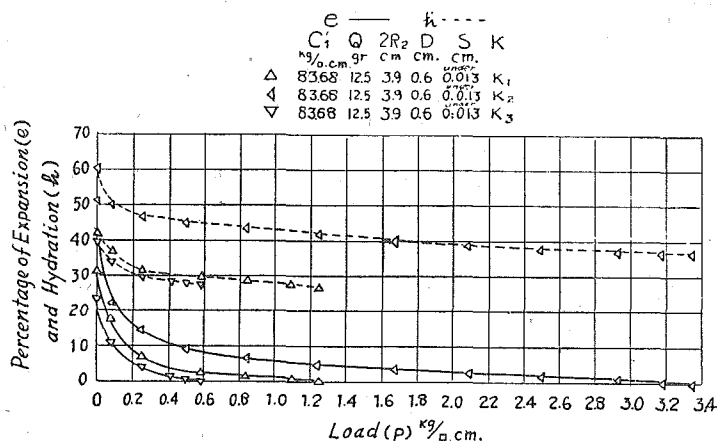


Fig. 12. Curves representing relationships among e , h and P' for three different Materials of K_1 , K_2 and K_3 .

with the Tanna sample K_1 , Hanaoka sample has always greater hydrous ratio, " h " and "Hydro-expansion" ratio " e " and, on the contrary Fushun sample has always smaller ones.

In short, although the tests are made under quite the same conditions, the difference in absorbent materials exerts a effect on the testing results.

Considering from the above results, even in the actual cases, such as tunnel and adit, phenomenon of "Hydro-expansion" may also be influenced by the kind of materials. When the materials are different, a sample with greater hydrous ratio may have a greater volume change due to hydration and also it may have stronger expansive power.

With the many other kinds of materials similar tests have been made. For example, glass powder was tested and even in this case, phenomenon of "Hydro-expansion" was observed plainly.

In the present paper, the tested results concerned with only three kinds of materials were given as the typical examples. And in the already mentioned tests, they were investigated changing only one condition. Regarding the other correlations obtained from combination of the several test conditions, they will be studied hereafter.

Chapter VI. RELATIONSHIP BETWEEN E ("HYDRO-EXPANSION") AND TESTING CONDITIONS.

In Tests I to V, observations were made on the effects of (I) initial compression applied to material, (II) quantity of test material and (III) compression applying on test piece during hydration upon the "Hydro-expansion" " E ". Furthermore, effects of (IV) powder-block size and (V) kind of material upon the relation between E and P have been examined. In brief, the tests hitherto described have already supplied data on the following relations:

- (I) $E : C$
 (II) $E : Q$
 (III) $E : P$
 (IV) $E : P : S$
 and (V) $E : P : K$

The relations to be described hereafter are as follows :

- (VI₁) $E : C : Q$
 (VI₂) $E : P : C$
 and (VI₃) $E : P : Q$

In these relations, powder-block size "S" and kind of material "K" were limited to S_1 and K_1 .

**(VI₁) Relationship between E ("Hydro-expansion") and
C (Initial Compression) for different quantities
of Test Material.**

Test Material. Test material was Tanna clay K_1 having the powder block size of S_1 (under 0.01 cm³).

Test Pieces. Quantity of materials "Q", initial compression of test pieces "C" and diameter of cylindrical plate-formed test pieces "2R" were determined as follows :

- (a) $Q_1 = 6.25$ gr., $C_1 = 1$ ton ($C' = 174.52$ kg/cm²), $2R_1 = 2.7$ cm ;
 (b) $Q_2 = 12.5$ gr., $C_1 = 1$ ton ($C' = 83.68$ kg/cm²), $2R_2 = 3.9$ cm ;
 (c) $Q_3 = 25.0$ gr., $C_1 = 1$ ton ($C' = 40.60$ kg/cm²), $2R_3 = 5.6$ cm.

of these three different test pieces three each were made. Thickness of test pieces became all 0.6 cm.

Two other kinds of test pieces were made for reference as follows :

- (d) $Q_1 = 6.25$ gr., $C_1 = 1$ ton ($C' = 83.68$ kg/cm²), $2R_2 = 3.9$ cm.
 (e) $Q_2 = 25.0$ gr., $C_1 = 1$ ton ($C' = 83.68$ kg/cm²), $2R_2 = 3.9$ cm.

In these test pieces, the thickness became respectively 0.3 cm. and 1.2 cm.

Testing Apparatus. Three sets each of large ($2R_3 = 5.6$ cm.), medium ($2R_2 = 3.9$ cm.) and small ($2R_1 = 2.7$ cm.) sized "Hydro-expansion" testing apparatuses were used.

Testing Treatment. At first using the test pieces (a), (b) and (c) and next (d) and (e), "Hydro-expansion" "E" and absorbing water H under no load during hydration were tested.

Test Results. Already obtained results for test pieces (b), (d) and (e) are quoted here without repeating the tests.

Table 12. Relationships among e , h and C for different quantities of material.

Nos.	Q gr.	$2R$ cm.	D cm.	C' kg/cm ² .	(β)		(α)	
					H gr.	h %	d cm.	e %
(a)	6.25	2.7	0.6	174.52	2.44	39.04	0.200	33.33
(b)	1.25	3.9	0.6	83.68	5.22	41.76	0.185	30.83
(c)	25.0	5.6	0.6	40.60	11.47	45.88	0.164	27.33
(d)	6.25	3.9	0.3	83.68	3.33	53.28	0.134	44.67
(e)	25.0	3.9	1.2	83.68	8.62	34.47	0.189	15.75

Q = quantity of test material;

$2R$ = diameter of cylindrical plate-formed test piece;

D = thickness of test piece;

C' = initial compression per unit area;

H = weight of absorbed water;

h = hydrous ratio;

d = thickness change of test piece during hydration;

e = percentage of thickness change;

No. (b) = No. XVI in Test II and No. XVI₁ in Test III;

No. (d) = No. XVI in Test II;

No. (e) = No. XVII in Test II.

For convenience of investigation tested results in Test VI are to be classified into two groups of Nos. (a), (b) and (c) and Nos. (d) (b) and (e). In the former group, quantities " Q " in three different kinds of test pieces were taken at the ratio of 1:2:4. Circular areas of test pieces were also made at the nearly same ratio of 1:2:4 and initial compressions per unit area were taken nearly inversely proportional to the ratio of 1:2:4. Consequently the thickness became uniformly equal. Absorbed water remarkably increased with the increment of quantity of material and on the contrary "Hydro-expansion" decreased with that increment. That is, in No. (a) H is small and d is great on account of its small quantity and large intensity of initial compression, in No. (c) contrariwise H is large and d is small, and in No. (b) the values lie median to the above two cases. Regarding to h and e , similar results were obtained.

In the latter group, quantities of Nos. (d), (b) and (e) were taken at the ratio of 1:2:4 as the former which circular areas of test pieces were made equal and consequently the intensity of initial compression became the same. Then the ratio of the thickness became 1:2:4. In this case, H and d increased with the increment of the thickness and h and e decreased on the contrary:

The above relations between "Hydro-expansion" and quantity of material are graphed as shown in Fig. 13.

In the figure, Δ_1 , Δ_2 and Δ_3 are respectively for Nos. (a), (b) and (c) and $\circ$ and $\square$ represent respectively Nos. (d), (b) and (e).

In this test the latter group of Nos. (d), (b) and (e) was tested merely for reference and the test on the former group is, indeed, the chief point. And the relations among Nos. (a), (b) and (c) are thus as already mentioned:

In the test piece having the smaller quantity of material and larger intensity of initial compression, the percentage of "Hydro-expansion" " e " is greater and percentage of absorbed water " h " is smaller than in those having the greater quantity of material and smaller intensity of initial compression and yet this tendency is more evident than in the test which is made keeping C' at constant value of 83.68 kg/cm² and increasing the quantity of material.

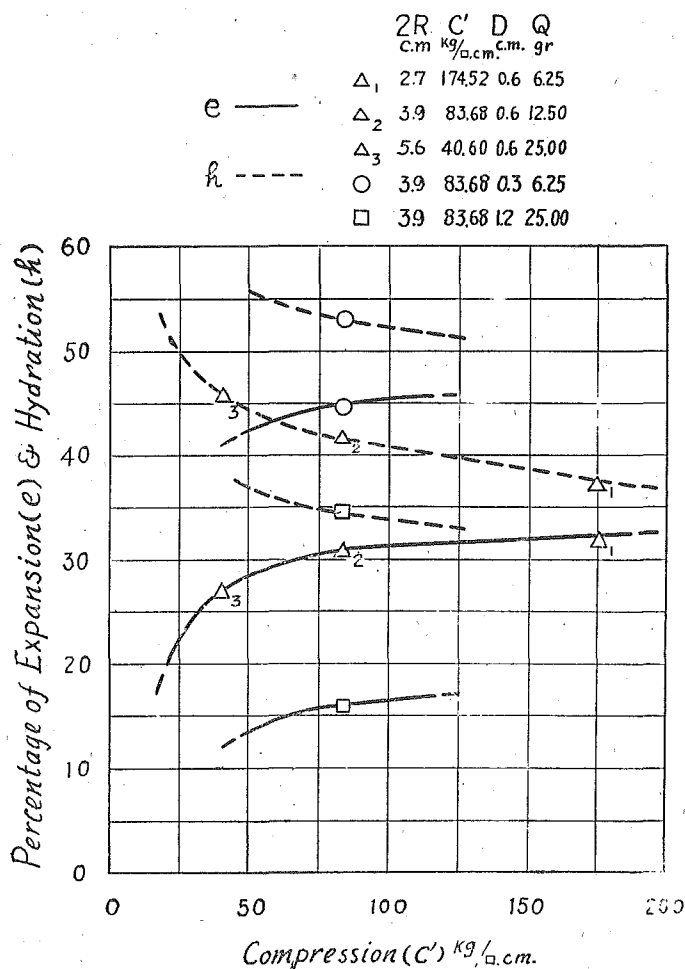


Fig. 13. Curves showing relationships among e , h and C' for different Quantities of material.

(VI₂). Relationship between E ("Hydro-expansion") and P
(Applied Compression During Hydration) for
Different Initial Compressions.

Test Material. Test piece material is Tanna clay K_1 having the powder-block size of S_1 (under 0.01 cm^3 .) as the preceding test.

Test Pieces. Quantities of test pieces Q were all taken to $Q_2 = 12.5 \text{ gr.}$ and every test piece was made into cylindrical plate-form having the diameter of $2R_2 = 3.9 \text{ cm.}$ These test pieces were divided into three groups which were given three different initial compressions such as $C_1 = 1 \text{ ton}$ ($C' = 83.68 \text{ kg/cm}^2$.), $C_2 = 2 \text{ tons}$ ($C' = 167.36 \text{ kg/cm}^2$.), and $C_3 = 3 \text{ tons}$ ($C' = 251.04 \text{ kg/cm}^2$.) and thereby the thickness of test pieces became respectively 0.6 cm. , 0.53 cm. and 0.5 cm.

Testing Apparatus. In this test three sets of the medium-sized "Hydro-expansion" testing apparatuses were used.

Testing Treatment. For comparing and contrasting the present testing results with those in Test III, test material, testing pieces, testing apparatus and testing treatment were under exactly the same conditions as in Test III.

Test Results. Tested results became as shown in Table 16.

Table 16. Relationships among e , h and P for different
Initial Compressions.

Nos.	$P \text{ kg/11.95 cm}^2$.	$P \text{ kg/cm}^2$.	(β)		(α)	
			$H \text{ gr.}$	$h \%$	$d \text{ cm.}$	$e \%$
XVI ₁	0	0	5.22	41.76	0.185	30.83
XVI _a ₁	0	0	4.85	38.80	0.175	33.00
XVI _b ₁	0	0	4.75	38.00	0.167	33.40
XVI ₂	1	0.084	4.63	37.00	0.109	18.17
XVI _a ₂	1	0.084	....	....	....	....
XVI _b ₂	1	0.084	....	....	....	....
XVI ₄	3	0.251	3.90	31.20	0.040	6.67
XVI _a ₄	3	0.251	3.57	28.56	0.055	10.30
XVI _b ₄	3	0.251	3.50	28.00	0.052	10.40
XVI ₅₋₆	6	0.502	....	....	....	....
XVI _a ₅₋₆	6	0.502	3.35	26.80	0.040	7.55
XVI _b ₅₋₆	6	0.502	3.25	26.00	0.039	7.80
XVI ₆	7	0.586	3.68	29.44	0.014	2.33
XVI _a ₆	7	0.586	....	....	....	....
XVI _b ₆	7	0.586	....	....	....	....

Table 16.—*Continued.*

Nos.	P kg/11.95 cm ² .	P kg/cm ² .	(β)		(α)	
			H gr.	h %	d cm.	e %
XVI ₇	10	0.837	3.55	28.40	0.010	1.67
XVI _{a7}	10	0.837	3.22	25.76	0.024	4.53
XVI _{b7}	10	0.837	3.05	24.40	0.027	5.40
XVI ₈	13	1.088	3.43	27.44	0.002	0.38
XVI _{a8}	13	1.088	....	....	....	....
XVI _{b8}	13	1.088	....	....	....	....
XVI ₉	15	1.255	3.33	26.64	0	0
XVI _{a9}	15	1.255	3.15	25.20	0.018	3.39
XVI _{b9}	15	1.255	2.88	23.04	0.020	4.00
XVI ₁₀	20	1.674	....	....	....	....
XVI _{a10}	20	1.674	3.00	24.00	0.012	2.26
XVI _{b10}	20	1.674	2.75	22.00	0.014	2.80
XVI ₁₁	25	2.092	....	....	....	....
XVI _{a11}	25	2.092	2.83	22.64	0.007	1.32
XVI _{b11}	25	2.092	2.70	21.60	0.012	2.40
XVI ₁₂	28	2.343	....	....	....	....
XVI _{a12}	28	2.343	2.77	22.16	0.003	0.56
XVI _{b12}	28	2.343	....	....	....	....
XVI ₁₃	30	2.510	....	....	....	....
XVI _{a13}	30	2.510	2.70	21.60	0	0
XVI _{b13}	30	2.510	2.56	20.48	0.010	2.00
XVI ₁₄	35	2.929	....	....	....	....
XVI _{a14}	35	2.929	....	....	....	....
XVI _{b14}	35	2.929	2.50	20.00	0.008	1.60
XVI ₁₅	40	3.347	....	....	....	....
XVI _{a15}	40	3.347	....	....	....	....
XVI _{b15}	40	3.347	2.45	19.60	0.007	1.40
XVI ₁₆	45	3.766	....	....	....	....
XVI _{a16}	45	3.766	....	....	....	....
XVI _{b16}	45	3.766	2.31	18.48	0.005	1.00
XVI ₁₇	50	4.184	....	....	....	....
XVI _{a17}	50	4.184	....	....	....	....
XVI _{b17}	50	4.184	2.25	18.00	0.004	0.80
XVI ₁₈	55	4.602	....	....	....	....
XVI _{a18}	55	4.602	....	....	....	....
XVI _{b18}	55	4.602	2.20	17.60	0	0

P = applied load on circular area of 11.95 cm^2 . of test piece during hydration;

P' = applied compression per unit area;

H = weight of absorbed water;

h = hydrous ratio;

d = thickness change of the test piece during hydration;

e = percentage of thickness change;

$C_1' = 83.68 \text{ kg/cm}^2$, $D = 0.6 \text{ cm}$. for Nos. XVI₁ to XVI₁₈;

$C_2' = 167.36 \text{ kg/cm}^2$, $D = 0.53 \text{ cm}$. for Nos. XVI_{a1} to XVI_{a18};

$C_3' = 251.04 \text{ kg/cm}^2$, $D = 0.5 \text{ cm}$. for Nos. XVI_{b1} to XVI_{b18};

In Table 16, the obtained results of Nos. XVI₁ to XVI₁₈ are quoted from Test III. Comparing these results with those which were obtained from the two groups of Nos. XVI_{a1} to XVI_{a18} and Nos. XVI_{b1} to XVI_{b18} special attention is attracted as follows:

In the test pieces having equal quantity of material and equal compression during hydration, "Hydro-expansion" " E " and absorbed water " H " are effected by even the magnitude of initial compression.

A test piece with greater C shows greater percentage of "Hydro-expansion" " e " and smaller percentage of absorbed water. At the same time, when compression of over a certain definite value is applied during hydration, every test piece absorbs water but "Hydro-expansion" ceases to appear as the "Hydro-expansive power" is overcome by the applied compression and when the greater initial compression is given the test piece can bear a greater load, that is, it has a stronger "Hydro-expansive power" ϵ .

Perhaps, quantitative conclusion may be rash still but the following relations can be observed:

Let P_1 , P_2 and P_3 be respectively the applied compression during hydration, because of which the "Hydro-expansion" begins to cease, for the three kinds of test pieces with initial compression of C_1 , C_2 and C_3 or C_1' , C_2' and C_3' having the ratio of 1:2:4 and let ϵ_1 , ϵ_2 and ϵ_3 be respectively the "Hydro-expansive powder" on these occasions.

Then, $P_1:P_2:P_3 = [\epsilon_1]:[\epsilon_2]:[\epsilon_3]$

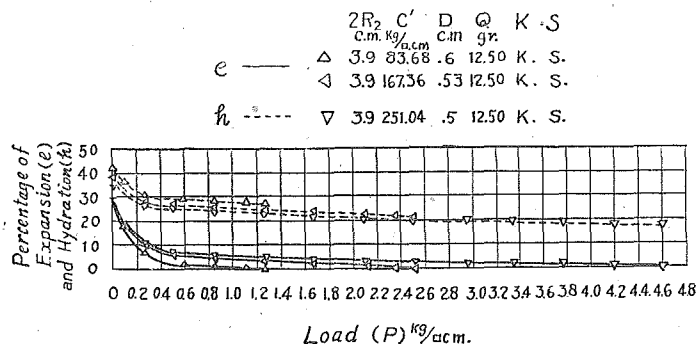
and there ratios become as follows:

$$15:30:55 \text{ or } 1.255:2.510:4.602 = 1:2:3.667.$$

This is the quantitative relation obtained from the tested results and it teaches that "Hydro-expansive powder" ϵ is approximately proportional to the magnitude of initial compression C .

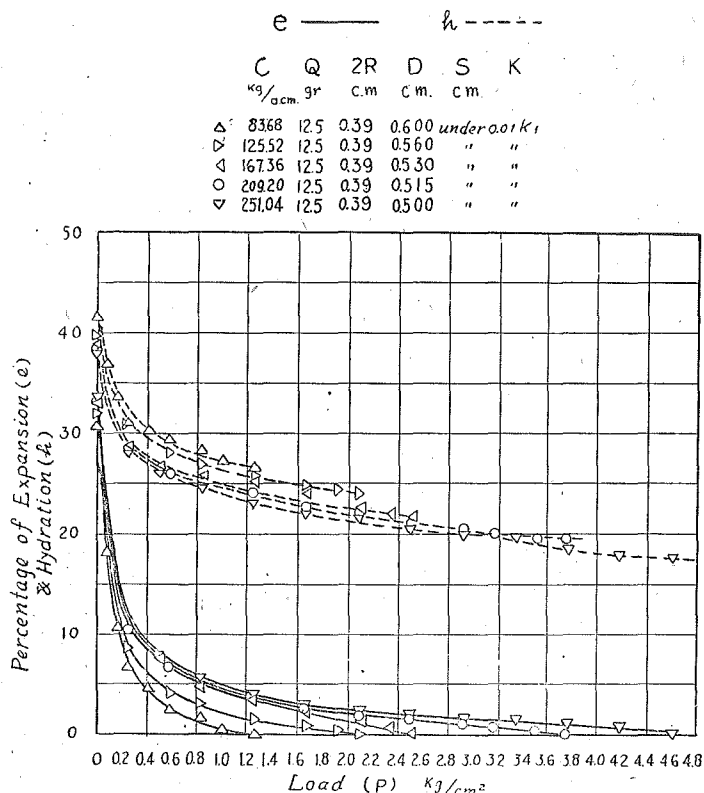
Curves showing relationships among e , h and P for the three kinds of test pieces having the different initial compression C' are represented in Fig. 14.

In the figure, two curves of $e:P$ and $h:P$ run parallel with each other and from these curves following conclusion can be drawn.

Fig. 14. Curves showing relationships among e , h and P for different Initial Compressions.

When no load is applied during hydration, a test piece given greater initial compression C' always shows greater percentage of "Hydro-expansion" " e " and smaller percentage of absorbed water " h ".

This fact is also true even in the case when any load is applied on the test piece during its hydration.

Fig. 14'. Curves showing relationships among e , h and P for different Initial Compressions.

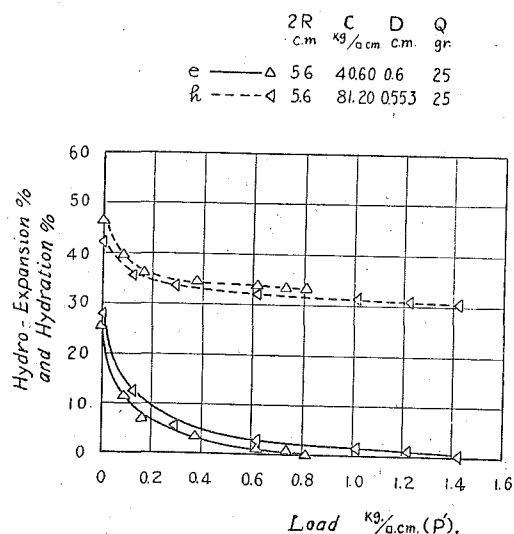


Fig. 14''. Curves showing relationships among e , h and P for different Initial Compressions.

Outward appearance of curves is Fig. 14 seems to resemble the appearance of curves obtained in Test V for three different kinds of materials but the arrangement of the curves of $h:P$ becomes reversed in comparison with the one in Test V showing the difference between them.

As this test was very important, many other tests have been made and some results of them will be shown here by means of figures.

Fig. 14' for the test results obtained with the five test piece having different initial compressions of $C' = 83.86 \text{ kg/cm}^2$; 125.52 kg/cm^2 ; 167.36 kg/cm^2 ; 209.20 kg/cm^2 and 251.04 kg/cm^2 .

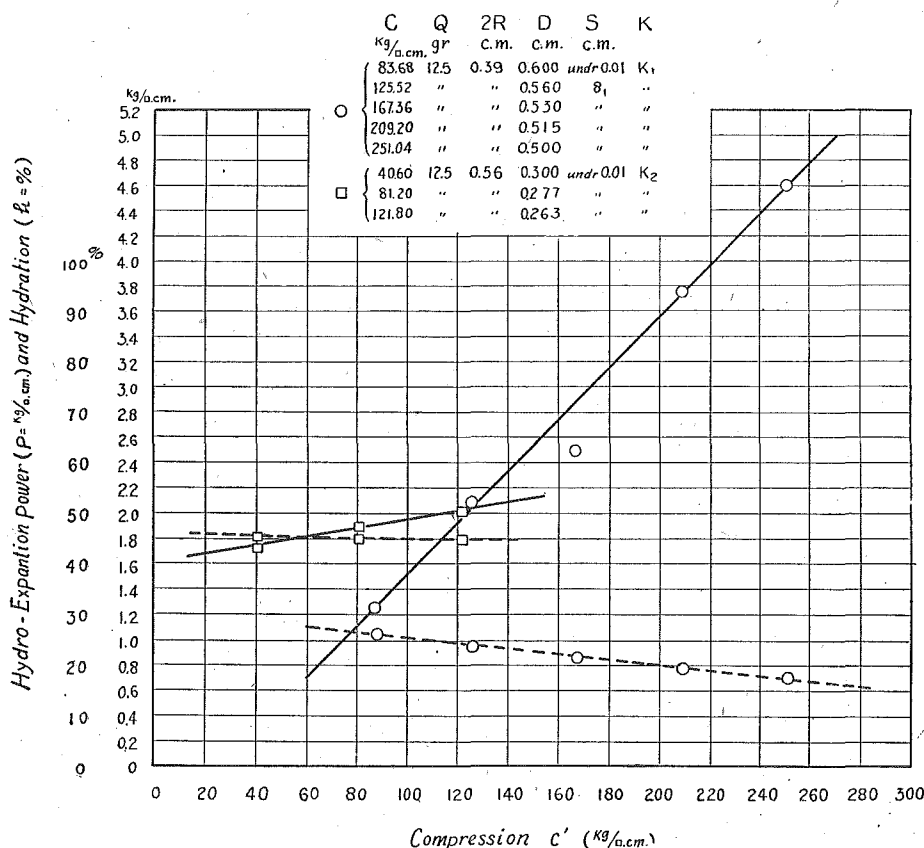


Fig. 14'''. Curves showing relationships among C' , P' and h .

251.04 kg/cm². under the same conditions as the above tests. Every test result is represented with a similarly curve to the one in Fig. 14 and thereby it is recognized that all relations show resemblance to each other.

Fig. 14'' is for the test results obtained from two test pieces with initial compressions of $C' = 40.60$ kg/cm². and 81.20 kg/cm²., having the diameter of $2R = 5.6$ cm. and double the quantity of material in eth preceding test.

This figure also shows similar properties and relations to the former ones, and when the initial compression is greater, the expansive power also becomes greater.

Fig. 14''' shows the relations between the initial compression " C' " and expansive power " ϵ ", i.e. the minimum P' by which "Hydro-expansion" is caused to begin in cease.

In the figure, there are shown the relation obtained from two kinds of materials, Tanna clay " K_1 " and Hanaoka clay " K_2 ".

The relation between initial compression " C' " and expansive power " ϵ " can be represented by a straight line as shown in the figure and ϵ is directly proportional to C' . The relation between initial compression " C' " and percentage of absorbed water " h " can also be represented by a straight line h is inversely proportional to C' .

As to Tanna clay and Hanaoka clay, their results are represented by different straight lines.

(VI₃) Relationship between E ("Hydro-expansion") and P (Compression Applied During Hydration) for Different quantities for Test Material.

Test Material. Material K_1 having the powder-block size S_1 was used the same as in the preceding test.

Test Pieces. Three different kinds of test pieces having the different quantities of $Q_1 = 6.25$ gr., $Q_2 = 12.5$ gr. and $Q_3 = 25.0$ gr. respectively were made. The diameter was made equal $2R_2 = 3.9$ cm. These cylindrical plate-formed test pieces were all equally compressed with $C_1 = 1$ ton or $C_1' = 83.68$ kg/cm². making their thicknesses be respectively $D_1 = 0.3$ cm.; $D_2 = 0.6$ cm. and $D_3 = 1.2$ cm. Thereby, three groups of test pieces were made and tested having the equal C and $2R$ and three different quantities and thicknesses taken at the ratios of $Q_1:Q_2:Q_3 = 1:2:4$ and $D_1:D_2:D_3 = 1:2:4$.

Testing Apparatus. Three sets of medium-sized "Hydro-expansion" testing apparatuses were used as in the preceding test.

Testing Apparatus. Same as the preceding test.

Test Results. Results are shown first in the table and then in figure followed by explanation.

Table 17. Relationships among e , h and P for different Quantities of Material.

Nos.	P kg/11.95 cm ²	P' kg/cm ²	(β)		(α)	
			H gr.	h %	d cm.	e %
XV ₁	0	0	3.33	53.28	0.134	44.67
XVI ₁	0	0	5.22	41.76	0.185	30.83
XVII ₁	0	0	8.62	34.47	0.189	15.75
XV ₂	1	0.084	....	....	....	....
XVI ₂	1	0.084	4.63	37.00	0.109	18.17
XVII ₂	1	0.084	....	....	....	....
XV ₄	3	0.251	2.73	43.68	0.035	11.67
XVI ₄	3	0.251	3.90	31.20	0.040	6.67
XVII ₄	3	0.251	7.52	30.08	0.064	5.33
XV ₅	5	0.418	2.52	40.32	0.017	5.67
XVI ₅	5	0.418	....	....	....	....
XVII ₅	5	0.418	....	....	....	....
XV ₅₋₆	6	0.502	....	....	....	....
XVI ₅₋₆	6	0.502	....	....	....	....
XVII ₅₋₆	6	0.502	7.05	28.20	0.052	4.33
XV ₆	7	0.586	....	....	....	....
XVI ₆	7	0.586	3.68	29.44	0.014	2.33
XVII ₆	7	0.586	....	....	....	....
XV ₆₋₇	8	0.669	2.40	38.40	0.006	2.50
XVI ₆₋₇	8	0.669	....	....	....	....
XVII ₆₋₇	8	0.669	....	....	....	....
XV ₇	10	0.837	2.38	38.08	0	0
XVI ₇	10	0.837	3.55	28.40	0.010	1.67
XVII ₇	10	0.837	6.63	26.52	0.039	3.25
XV ₈	13	1.088	....	....	....	....
XVI ₈	13	1.088	3.43	27.44	0.002	0.38
XVII ₈	13	1.088	....	....	....	....
XV ₉	15	1.255	....	....	....	....
XVI ₉	15	1.255	3.33	26.64	0	0
XVII ₉	15	1.255	6.05	24.20	0.016	1.33
XV ₁₀	18	1.506	....	....	....	....
XVI ₁₀	18	1.506	....	....	....	....
XVII ₁₀	18	1.506	6.00	24.00	0.004	0.33
XV ₁₁	20	1.674	....	....	....	....
XVI ₁₁	20	1.674	....	....	....	....
XVII ₁₁	20	1.674	5.82	23.28	0	0

P = applied compression on circular area of 11.95 cm^2 . of test piece during hydration;

P' = applied compression per unit area;

H = weight of absorbed water;

h = hydrous ratio;

d = thickness change of test piece during hydration;

e = percentage of thickness change;

$Q_1 = 6.25 \text{ gr.}$, $D_1 = 0.3 \text{ cm.}$ for test pieces of Nos. XVI₁ to XV₁₁;

$Q_2 = 12.5 \text{ gr.}$, $D_2 = 0.6 \text{ cm.}$ for test pieces of Nos. XVI₁ to XVI₁₁;

$Q_3 = 25.0 \text{ gr.}$, $D_3 = 1.2 \text{ cm.}$ for test pieces of Nos. XVII₁ to XVII₁₁.

Nos. XV₁; XVI₁ and XVII₁ are the same respectively as Nos. XV, XVI, and XVII in Test II and thereby results concerned with them were quoted from Test II.

In Table 17, Nos. XVI₁ to XVI₁₁ have already been tested in Test III and comparing with those, two other groups of pieces were tested newly in the present experiment. Let the percentage of "Hydro-expansive power" be respectively e_1 , e_2 , e_3 and $[\epsilon_1]$, $[\epsilon_2]$, $[\epsilon_3]$ for three groups of test pieces having the different quantities taken at the ratio $Q_1:Q_2:Q_3 = 6.2:12.5:25.0 = 1:2:4$. Then, in the case of no load P the ratio of $e_1:e_2:e_3$ becomes $44.67:30.83:15.75 = 3:2:1$ and the ratio of $[\epsilon_1]:[\epsilon_2]:[\epsilon_3]$ becomes $0.837:1.255:1.674 = 2:3:4$ as obtained from Table 17.

The diagrammatic relations among these e , h and P become as shown in Fig. 15.

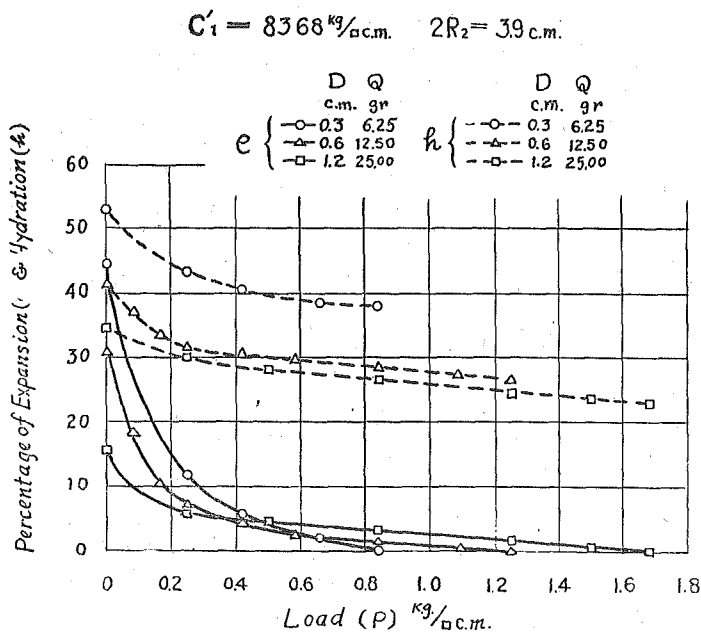


Fig. 15. Curves showing relationships among e , h and P for different Quantities of Material.

In the figure, curves of $e:P$ intersect each other showing resemblance to the results in Test IV which were obtained for different powder-block size of material. This fact can be interpreted thus:

In the test piece with small quantity of material, percentage of "Hydro-expansion" e is great for the small load P and e rapidly decreases with increase of P . While on the contrary, in the test piece with large quantity of material e is small for small load P and e slowly decreases with increases of P .

Curves of $h:P$ bear also a close resemblance to those in Test IV and they are similar to relations in the preceding test which was made changing the initial compression, too.

Many other tests besides the above described have been made, but all of their results confirmed the above stated relations.

For a comparison of Tanna clay K_1 to Hanaoka clay K_2 , the latter one was tested with results shown in Fig. 15'.

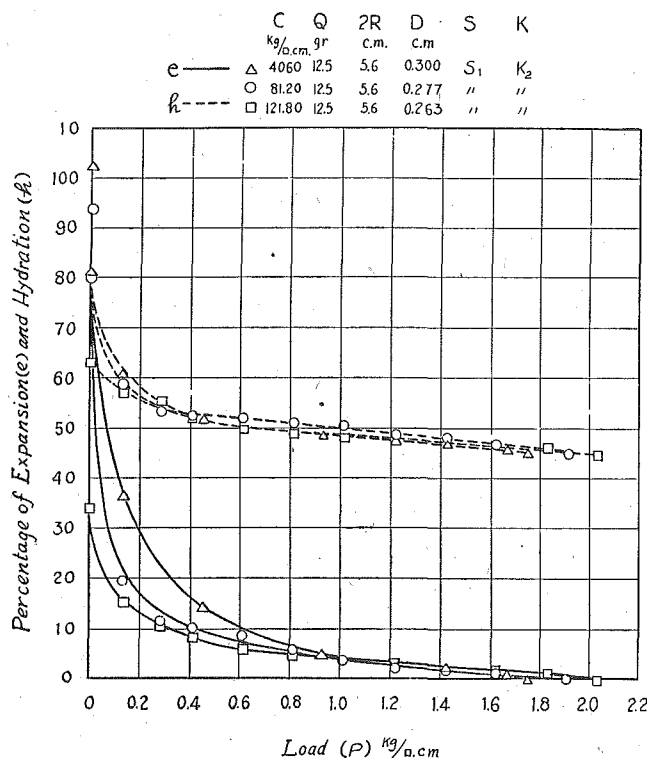


Fig. 15'. Curves showing relationships among e , h and P for different Quattie of Material.

In this test, quantity of material was taken nearly equal to the former one but large-sized testing apparatus was used and initial compression C was decreased to half. While all of the relations became similar to those in Tanna clay and in Fig. 15' three curves of $e:P$ intersected each other and curves of $h:P$ did not intersect as those for Tanna clay K_1 .

From Fig. 15' load P' by which expansion begins to cease for three kinds of test pieces having different quantities of 37.5 gr.; 25.0 gr. and 12.5 gr. is respectively 2.274 kg/cm^2 ; 2.03 kg/cm^2 . and 1.75 kg/cm^2 . and percentage of absorbed water h are respectively 45.20 %; 38.60 % and 34.00 %.

In Figure 15'', the above relations are shown and each one of them is represented by a straight line showing that when quantity Q is greater expansive power ϵ is also greater and the percentage of absorbed water becomes smaller on the contrary.

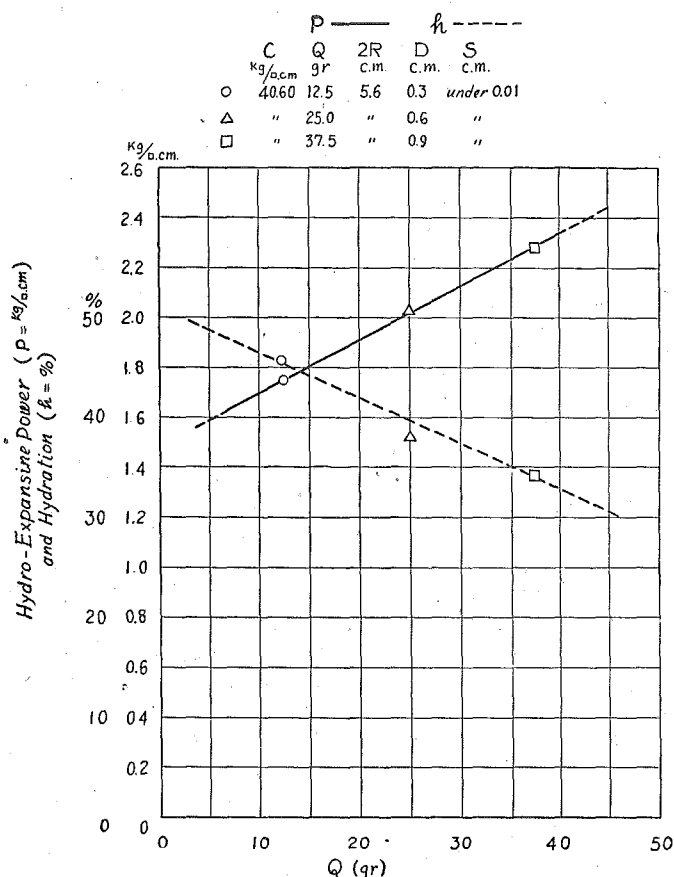


Fig. 15''. Curves showing relationships among P , h and Q .

As the "Hydro-expansion" phenomenon under all conditions of test material and piece have been investigated, summarizing and adding more explanation, some general conclusions will be drawn in a latter paper.

SUMMARY AND CONCLUSIONS.

(Appendix : Experimental Formulae).

Summary.

As already stated, these studies have been made for an inquiry into the so-called "earth-pressure" which appeared gradually and yet severely in the clay zone of Tanna tunnel destroying timbering work when that clay zone, which was compressed in dry state at first when it occurred in the tunnel, was excavated and then absorbed water.

In the tests, clay exhibited a phenomenon of "Hydro-expansion" being accompanied with the increase of the apparent volume of clay and consequently with "Hydro-expansive power".

For the investigation of the so-called "earth-pressure" due to "Hydro-expansion", experimental conditions were reproduced as similar as possible to the natural state.

Letting one side of a test piece touch with a water and the other side be free or compressed by a certain load, "Hydro-expansion", hydration, "Hydro-expansive power" etc. were tested under many different conditions in order to find a key to solve the actual problems concerned with "earth-pressure".

Compressing completely dry powdered clay in a gun-metal cylindrical tube by a 60 tons compression testing machine, cylindrical plate-formed test pieces were made. These test pieces were taken into the same cylindrical tube as used for making and some water allowed to soak into the inside of the tube from the base through net and filtering paper.

For the purpose of measurements of thickness change and expansive power the author's "Hydro-expansion" testing apparatus was used.

Regarding the results, they may be summarized as below using the following conventional symbols:

- E = "Hydro-expansion" or thickness change of test piece due to hydration,
- C = initial compression given to test piece before hydration,
- C' = initial compression per unit area,
- P = applied compression load on test piece during hydration,
- P' = applied compression load per unit area,
- S = powder-block size of test material,
- K = kind of material,
- $2R$ = diameter of cylindrical plate-formed test piece,
- D = thickness of test piece before hydration,
- d = thickness change of test piece during hydration,
- e = percentage of thickness change or, briefly, expansion ratio,
- H = weight of absorbed water,
- h = percentage of absorbed water or, briefly, hydrous ratio,
- $[\epsilon]$ = "Hydro-expansive power".

(I). Relationships Between E and C .

Conditions: $K = K_1 = \text{Tanna clay,}$
 $S = S_1 = \text{under } 0.01 \text{ cm}^3,$
 $Q = Q_2 = 12.5 \text{ gr.},$
 $2R = 2R_1 = 2.7 \text{ cm.},$
 $D = 0.8 \sim 2.4 \text{ cm.},$
 $P = 0.$

- (1). E does not appear when $C' = 1.745 \text{ kg/cm}^2$. or less and on the contrary clay contracts itself during hydration.
- (2). In case $C' = 8.73 \text{ kg/cm}^2$. or more, E appears and the greater C is, the more plainly does E appear.
- (3). In case $C' < 174.52 \text{ kg/cm}^2$., e increases rapidly with the increase of C .
- (4). When $C' > 174.52 \text{ kg/cm}^2$., e increases gradually with the increase of C .
- (5). e shows an upward tendency till $C' = 4013.96 \text{ kg/cm}^2$. Regarding h , it decreases more rapidly in test piece of greater C representing an opposite tendency to e . (See Main Test I.)

(II). Relationships Between E and Q .

Conditions: $K = K_1,$
 $S = S_1,$
 $C = C_1 = 1 \text{ ton } (C' = 83.68 \text{ kg/cm}^2),$
 $2R = 2R_2 = 3.9 \text{ cm.},$
 $P = 0.$

- (6). e is greater in $Q = 6.25 \text{ gr.}$ than in $Q = 1.25 \text{ gr.}$
- (7). e is greater in $Q = 12.5 \text{ gr.}$ than in $Q = 25 \text{ gr.}$

In this test, Q and D are in directly preportional relation when C is constant and in three test pieces having the ratio of 62.5:12.5:25 or 1:2:4 in their quantities Q , the ratio of their D becomes also 3:6:12 or 1:2:4. Relation between h and Q is similar to that between E and Q , and h decreases with the increase of Q . (See Main Test II.)

(III). Relationships Between E and P .

Conditions: $K = K_1,$
 $S = S_1,$
 $C = C_1,$
 $Q = Q_2,$
 $2R = 2R_2,$
 $D = D_2.$

- (8). e decreases at a certain rate with the increase of P .
- (9). E can not appear when $P' = 1.255 \text{ kg/cm}^2$. or more.
- (10). E is accompanied by $[\varepsilon]$ to resist P and strength of $[\varepsilon]$ is measured by P .

e and P are in the relation represented by a hyperbola. h and P are also in a similar relation to the former one and h decreases hyperbolically with the increase of P . Even when P reaches an amount at which E can not appear, h never become zero and absorbs a considerable amount of water.

Therefore absorbent materials do not always expand. (See Main Test III.)

(IV). Relationships Among E , S and P .

Conditions:

$$K = K_1,$$

$$C = C_1,$$

$$Q = Q_2,$$

$$2R = 2R_2,$$

$$D = D_2,$$

(11). e in the test piece of $S_2 = 0.02 \sim 0.05 \text{ cm}^3$. differs from that in one of S_1 .

(12). e in the test piece of $S_3 = 0.1 \sim 0.2 \text{ cm}^3$. differs also from that in one of S_2 .

(13). Three values of e in test pieces of S_1 ; S_2 and S_3 become equal to one another in case $P = 7 \text{ kg}$. ($P' = 9.585 \text{ kg/cm}^2$.)

(14). Under the same load P , the order of the amounts of e in case $P' < 0.565 \text{ kg/cm}^2$. becomes respectively S_1 ; S_2 , S_3 in decreasing order.

(15). Under the same load P as the above, the order of the amounts of e in case $P' > 0.585 \text{ kg/cm}^2$. becomes S_3 ; S_2 , S_1 in decreasing order.

(16). $[\epsilon]$ is varied due to S and the order of the magnitudes of $[\epsilon]$ becomes S_3 ; S_2 , S_1 in decreasing order.

(17). In case $P' < 0.585 \text{ kg/cm}^2$., $[\epsilon]$ is always greater in the test piece of a smaller e , that is, the order of magnitude of $[\epsilon]$ becomes S_3 , S_2 , S_1 in decreasing order.

Under the same load P , h is smaller in a test piece of greater S and three curves showing relationships between h and P for S_1 , S_2 and S_3 run nearly parallel to one another notwithstanding those of e and P intersect. (See Main Test IV.)

(V). Relationships Among E , K and P .

Conditions:

$$S = S_1,$$

$$C = C_1,$$

$$Q = Q_2,$$

$$2R = 2R_2,$$

$$D = D_2,$$

(18). e of K_2 (Hanaoka clay) is different from that of K_1 .

(19). e of K_3 (Fushun clay) is different from that of K_2 .

(20). Under the same load P , e of K_2 has always greater value than that of K_1 .

(21). Under the same load P , e of K_3 has always smaller value than that of K_1 .

- (22). $[\epsilon]$ of K_2 is much stronger than that of K_1 .
 (23). $[\epsilon]$ of K_3 is somewhat weaker than that of K_1 .
 (24). In case of $P=0$, K having greater e has always stronger $[\epsilon]$.

Under the same load P , h of K_2 is much greater than that of K_1 and h of K_3 is the smallest. Relationships among h , K and P has close resemblance to that among e , K and P and curves representing their relationship run parallel to one another for the most part. (See Main Test V.)

(VI₁). Relationship Among E , C and Q .

Conditions:

$$K = K_1,$$

$$S = S_1,$$

$$P = 0.$$

(25). e of a test piece (a) ($Q_1 = 6.25$ gr., $2R_1 = 2.7$ cm., $C_1 = 1$ ton or $C_a' = 175.52$ kg/cm²., $D_2 = 0.6$ cm.) is greater than that of a test piece (b) ($Q_2 = 12.5$ gr., $2R_2 = 3.9$ cm., $C_1 = 1$ ton or $C_b' = 83.68$ kg/cm²., $D_2 = 0.6$ cm.) by 2.5 %.

(26). e of a test piece (c) ($Q_3 = 25$ gr., $2R_3 = 5.6$ cm., $C_1 = 1$ ton or $C_c' = 40.60$ kg/cm²., $D_2 = 0.6$ cm.) is less than that of (b) by 3.5 %.

(27). e of a test piece (d) (Q_1 , $2R_2$, C_1 , C_b' , $D_1 = 0.3$ cm.), (b) and (e) (Q_3 , $2R_2$, C_1 , C_b' , $D_3 = 1.2$ cm.) is 44.67 %, 30.83 % and 15.75 % respectively and their ratio becomes approximately 3:2:1. Hence, the ratio of e is nearly inversely proportional to the ratio of quantities or thickness, viz. $Q_1:Q_2:Q_3 = 1:2:4$ or $D_1:D_2:D_3 = 1:2:4$.

H is smaller for smaller Q and greater C' and curves representing the relationships between e and C' and between h and C' show opposite aspects to each other, for the most part. (See Main Test VI₁).

(VI₂). Relationships Among E , C and P .

Conditions:

$$K = K_1,$$

$$S = S_1,$$

$$Q = Q_2,$$

$$2R = 2R_2,$$

(28). In case $P=0$, the amounts of e in the test pieces (b) ($C_1 = 1$ ton or $C_b' = 83.68$ kg/cm²., $D_2 = 0.6$ cm.), (f) ($C_2 = 2$ tons or $C_2' = 167.36$ kg/cm²., $D = 0.53$ cm.) and (g) ($C_3 = 3$ tons or $C_3' = 251.04$ kg/cm²., $D = 0.6$ cm.) are respectively 30.83 %, 33.00 % and 33.40 %. The last one has greatest but their difference are very small.

(29). In case $P = 10$ kg. ($P' = 0.837$ kg/cm².), the amounts of e in the above three test pieces are respectively 1.67 %, 4.53 % and 5.40 %. Still the last one has greatest e but their differences become greater than in the former case.

(30). The amounts of e in the above three test pieces become zero respectively in cases $P = 15$ kg, and 55 kg. ($P' = 1.255$ kg/cm²., 2.5 kg/cm². and

4.602 kg/cm²). These values of P are equal to the strongest expansive power $[\epsilon]$ and the ratio of $[\epsilon]$ in three different test pieces becomes 1:2:2.7. This ratio is nearly directly proportional to the ratio of C , viz., ratio or 1:2:3.

Regarding h , it decreases with the increase of P . Hence the relation between h and P is contrary to that between e and P .

(VI₃). Relationships Among E , Q and P .

Conditions:

$$\begin{aligned} K &= K_1, \\ S &= S_1, \\ C &= C_1, (C_b' = 83.68 \text{ kg/cm}^2.) \\ 2R &= 2R_2. \end{aligned}$$

(31). In three kinds of test pieces whose quantities of material are taken in ratio of 6.25:12.5:25 = 1:2:4, their thickness ratio becomes 0.3:0.6:1.2 = 1:2:4 and in case of $P = 0$, ratio of e among these three test pieces becomes 44.67:30.83:15.75 = 3:2:1 as already mentioned (See (28) in Test VI₁).

(32). When $P = 10$ kg. ($P' = 0.837$ kg/cm².) values of e in the above three test pieces are respectively 0 %, 1.67 % and 3.25 % and this ratio is the reverse to that in the above case.

(33). $[\epsilon]$ of the above three test pieces differ from one another and values of $[\epsilon]$ respectively 0.837 kg/cm²., 1.255 kg/cm². and 1.674 kg/cm²., ratio among which is 2:3:4, showing that $[\epsilon]$ is stronger in case of larger Q .

Under the same load P , h is smaller in case of larger p and h for smaller Q is greater than for larger Q , representing a close resemblance with the relation in Test VI₂.

Curves representing relationship between e and P intersect each other but curves for h and P run nearly parallel. (See Main Test VI₃).

CONCLUSIONS.

From the test concerned chiefly with the investigations of the phenomenon of "Hydro-expansion" and "expansive power" which is exhibited in accompany with "Hydro-expansion" of clay taken in Tanna tunnel under many kinds of conditions, general conclusions may be drawn as follows:

(a). The phenomenon of "Hydro-expansion" " E " in clay is sure to exist and it is affected by various conditions of clay.

(b). The phenomenon of "Hydro-expansion" " E " is observed when a clay is initially compressed by over a certain definite load before hydration. The apparent volume of clay before hydration is influenced by the initial compression " C " and volume change due to hydration has a directly proportional relation with that initial compression within a certain range of that amount.

Of course, in case of enormous initial compression, such as in a clay slate, no "Hydro-expansion" may be perceived and also, even in case when C is

under a certain definite amount, it is within the bounds of possibility that powdered clay settles and apparent volume decreases without swelling.

Therefore the occurrence of the phenomenon of "Hydro-expansion" in clay means that clay once has been placed under certain definite amount of compression and has a latent plasticity.

(c). In regard to the problem about the quantity of clay " Q ", it is needless to take it into consideration in case of a small quantity and a case of large one is preferably to be investigated. Hence, in the preliminary tests a large amount of Q was taken and many tests were carried out. But, when Q was large, total expansive power became so enormously large breaking the testing apparatus and causing the tests to fail so often that any results, from which general conclusions could be drawn, could not be obtained. Thus, the author was obliged to use small quantities such as described in Main Tests I to VI.

In a certain range of quantity, the larger the quantity of clay is, the smaller becomes the percentage of "Hydro-expansion" " e " and when the ratio of Q is 1:2:4, ratio of e becomes 3:2:1, representing nearly inverse proportional relation to each other, but in the above case, the ratio of maximum value of "Hydro-expansive power" " ϵ " becomes nearly 2:3:4 and it has a nearly direct proportional relation with the amount of Q .

That is to say *in case when a clay can exhibit "Hydro-expansion" with no restriction ($P=0$), apparent volume change of clay due to hydration is smaller in larger Q than in smaller Q but, on the contrary, expansive power becomes severer in the former case than in the latter and therefore when hydrous part of clay is great a force to resist the "Hydro-expansion" must be very strong.*

(d). Regarding the effect of powder-block size " S " upon "Hydro-expansion" " E ", if a free or nearly free absorption of water is permitted, percentage of volume change during hydration " e " is comparatively greater in case of smaller S . But, this "Hydro-expansion" can be more easily prevented. That is, *when a clay dries up and the more very fine grains it cracks into, the more the clay bulges out into a tunnel but the thrusting force is less.*

(e). The existence of the effect of the kind of clay " K " upon E is easily perceived. In case of $P=0$, $[\epsilon]$ for the clay of large E is strong and, on the contrary, $[\epsilon]$ for the clay of small E is weak. That is, under the same boundary conditions, Hanaoka clay exhibits the most evident "Hydro-expansion", Tanna clay the medium and Fushun clay the least. Regarding expansive power, there is the same relation among them.

Regarding the magnitude of "Hydro-expansive power" which is the most important among the points which the author wished to learn, it may be stated that *when a large quantity of dry clay has been initially strongly compressed to a certain definite degree and it has been made into a crackless large block, the apparent volume change due to hydration is not comparatively evident, but the expansive power is enormously strong. Furthermore it may be said that under quite the same conditions, every clay takes a different "Hydro-expansion" and "Hydro-expansive power" from every other according to its kind.*

APPENDIX.

Experimental Formulae.

In order to infer "Hydro-expansive power" " e " which is exhibited company with "Hydro-expansion" of a clay, apparent volume change was measured in Main Test III. From this measurement, it is known that percentage of "Hydro-expansion" " e " decreases with the increase of P and yet when load P reaches a certain limited value, the apparent volume of clay remains unchanged as already mentioned.

In this appendix, investigating mathematically the relation between e and P the author finds an experimental formula and then comparing the values calculated from this formula and the results of tests, further study is made as follows:

For convenience, P and e are respectively represented by x and y replacing the relation of $P:e$ by that of $x:y$. In Table 18, the results of tests and their logarithmic values are shown.

Table 18. Experimental values of P and e obtained from Main Test III and their Logarithmic Values.

$P \text{ kg/cm}^2$	$x(P \text{ kg/11.95 cm}^2)$	$y (e\%)$	$\log x \log P$	$\log y(\log e)$
0	0	30.83	0	1.4889
0.084	1	18.17	0.1000	1.2593
0.167	2	10.67	0.3013	1.0281
0.251	3	6.67	0.4771	0.8241
0.418	5	4.67	0.6989	0.6693
0.586	7	2.33	0.8450	0.3673
0.837	10	1.67	1.0000	0.2227
1.088	13	0.38	1.1139	0.0579
1.255	15	0	1.1760	0

As shown in Fig. 16, the relation between logarithmic values of x and y is represented approximately by a straight line ($\log x : \log y$).

In a similar way for other kinds of clay the same relation can be obtained. Figures concerned with them are omitted here.

y_c^m : calculated value from formula (9).

Plotting the experimental values of x and y , an experimental curve is obtained as shown in Fig. 16 with a broken line. When this experimental curve is folded back round a straight line passing through near a point of $x = 1.5$ on x -axis having the inclination of 45° from x -axis, the two parts of this curve lie one upon the other showing that this curve has symmetrical form having the above straight line as a symmetrical axis.

Therefore this experimental curve is supposed to be represented by a hyperbola, such as:

$$(y+\beta)(x+a)^n = \gamma \quad \dots\dots (A)$$

where α , β and γ are arbitrary constants.

Taking fit values for these constants, one can make $n = 1$. Hence the following simpler formula is supposed instead of the above formula;

$$(y+\beta)(x+a) = \gamma \quad \dots\dots (B).$$

Changing form, formula (B) becomes

$$y+\beta = \frac{\gamma}{a+x} \quad \dots\dots (1).$$

Putting the experimental values $x = 15$ and $y = 0$ into the above formula gives

$$\gamma = \beta(15+a)$$

Putting this relation into formula (1) and then dividing both sides by formula (1) becomes

$$\frac{y+\beta}{\beta} = \frac{a+15}{a+x} \quad \dots\dots\dots (2).$$

From formula (2),

$$\frac{y}{\beta} = \frac{a+x}{15-x} y$$

or

$$\beta = \frac{a+x}{15-x} y \quad \dots\dots\dots (3).$$

Next, putting the experimental values $x = 0$ and $y = y_0 = 30.83$ into formula (2) gives

$$\frac{y_0}{\beta} = \frac{15}{a} \quad \dots\dots\dots (4).$$

Form formula (2) and (4),

$$\frac{\frac{y}{y_0} 15}{a} = \frac{15-x}{a-x} = \frac{15-x-\frac{y}{y_0} 15}{x} = \frac{15\frac{y_0-y}{y_0}-x}{x} \quad \dots\dots\dots (5).$$

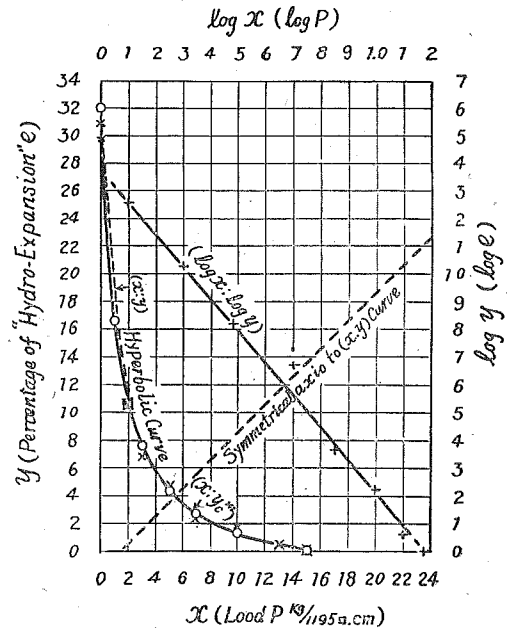


Fig. 16. Curves representing relationships of $x : y \log x : \log y$ and $x : y e^m$.

Therefore, α is represented as follow :

$$\alpha = \frac{y/y_0 15x}{15-x-y/y_0 15} \dots\dots\dots(6).$$

Putting the experimental values of Table 18 into formula (3) and (6), several numerical values of α and β are obtained. Taking mean values of them α and β are determined as follows :

$$\alpha = 1.4945,$$

$$\beta = 2.9499.$$

Corresponding value of γ to α and β is also determined from formula (B) as follow :

$$\gamma = 48.639.$$

Therefore, formula (B) becomes approximately

$$(y+3) (x+1.5) = 50 \dots\dots\dots(7).$$

Calculating the values of y for given values of x from the above formula, they become as shown in Table 19 with y_c^I and residuals also become as shown in the same table with Δ^I . Mean value of residuals is $\Sigma \Delta^I \div 9 = 0.525$.

Comparing these calculated values and experimental values of y , they coincide well with each other on the whole.

Using the above obtained values of α , β and γ as they stand instead of the approximate ones, the formula becomes

$$(y+2.95) (x+1.495) = 48.639 \dots\dots\dots(8).$$

Using the above formula, calculating values of y for given values of x become as shown in Table 19 with y_c^{II} and residuals Δ^{II} and their mean value $(\Sigma \Delta^{II} + 9)$ are shown in the same table.

In this case, calculated values and experimental values of y also coincide well with each other.

Nest, applying the theory of least square, formula (B) becomes

$$(y+2.576) (x+12.43) = 43.064 \dots\dots\dots(9).$$

The calculation process of formula (9) is omitted here.

Table 19. Calculating values of y , Residual and Mean Residual by various methods.

x	y	y_c^I	Δ^I	y_c^{II}	Δ^{II}	y_c^{III}	Δ^{III}
0	30.83	30.330	+0.500	29.530	+1.300	32.074	-1.244
1	18.17	17.000	+1.170	16.500	+1.670	16.625	+1.545
2	10.67	11.290	-0.620	10.920	-0.250	10.704	-0.034
3	6.67	8.110	-1.440	7.820	-1.150	7.574	-0.904
5	4.67	4.692	-0.022	4.468	+0.202	4.322	+0.348
7	2.33	2.882	-0.552	2.712	-0.382	2.649	-0.319
10	1.67	1.349	+0.321	1.228	+0.442	1.255	+0.415
13	0.38	0.448	-0.068	0.354	+0.026	0.448	-0.068
15	0	0.030	-0.030	-0.053	+0.053	0.075	-0.075
		$\Sigma \Delta^I \div 9 = 0.525$		$\Sigma \Delta^{II} \div 9 = 0.608$		$\Sigma \Delta^{III} \div 9 = 0.55$	

Using the above formula, the values of y for given values of x , residuals and mean residual become as shown in Table 19 respectively with y_c^{III} , Δ^{III} and ($\Sigma \Delta^{III} \div 9$).

Every curve of $x:y$ obtained using the calculated values has the similar form to one another and among them the last derived curve from the application of theory of the least square coincides best with the experimental curve. *The relation between the percentage of "Hydro-expansion" "e" and applied load "p" during hydration is surely represented by a hyperbola.*

POST-TESTS.

(I). "Hydro-expansion" of clay for Different Temperatures of Hydration.

As the temperature of hydration in Tanna tunnel was 19°C, "Hydro-expansion" of clay had always been investigated under the same temperature of hydration in the foregoing tests.

In the present section, effect of the temperature of hydration upon the "Hydro-expansion" of clay is described.

Test Material. Same as in Main Test III.

Test Pieces. Same as in Main Test III.

Testing Apparatus. Same in the Main Test III.

Testing Treatment. Same in the Main Test III.

Test Results. All the testing conditions were the same as in Main Test III excepting temperature of hydration. The results of test become as follows:

Table 20. Results on relationships among e , h and P for different Temperatures of Hydration.

Nos. of Samples	P kg./11.95 cm ² .	P' kg./cm ² .	(β)		(α)	
			H gr.	$h\%$	d cm.	$e\%$
XVI ₁	0	0	5.22	41.76	0.185	30.83
XVI ^{α} ₁	0	0	5.38	43.00	0.250	41.67
XVI ^{β} ₁	0	0	5.40	43.20	0.252	42.00
XVI ₂	1	0.084	4.63	37.00	0.109	18.17
.....						
.....						
XVI ₃	2	0.167	4.20	33.60	0.064	10.67
XVI ^{α} ₃	2	0.167	4.30	34.40	0.081	13.56
XVI ^{β} ₃	2	0.167	4.40	35.20	0.091	15.10
XVI ₄	3	0.251	3.90	31.20	0.046	6.67
.....						
.....						
XVI ₅	5	0.418	3.80	30.40	0.028	4.67
.....						
.....						
XVI ₆	7	0.589	3.68	29.44	0.014	2.33
XVI ^{α} ₆	7	0.586	3.85	30.80	0.032	5.33
XVI ^{β} ₆	7	0.586	4.00	32.00	0.036	6.00
XVI ₇	10	0.837	3.55	28.40	0.010	1.67
.....						
.....						
XVI ₈	13	1.088	3.43	27.44	0.002	0.38
.....						
.....						
XVI ₉	15	1.255	3.33	26.64	0	0
XVI ^{α} ₉	15	1.255	3.65	28.20	0.009	1.44
XVJ ^{β} ₉	15	1.255	3.70	29.60	0.015	2.50
.....						
XVI ^{α} ₁₀	17	1.423	3.60	28.80	0.008	1.28
.....						
.....						
XVI ^{α} ₁₁	19	1.590	3.60	28.80	0.005	0.83
.....						
.....						
XVI ^{α} ₁₂	22	1.841	3.45	27.60	0.002	0.35
XVI ^{β} ₁₂	22	1.841	3.60	28.80	0.008	1.33

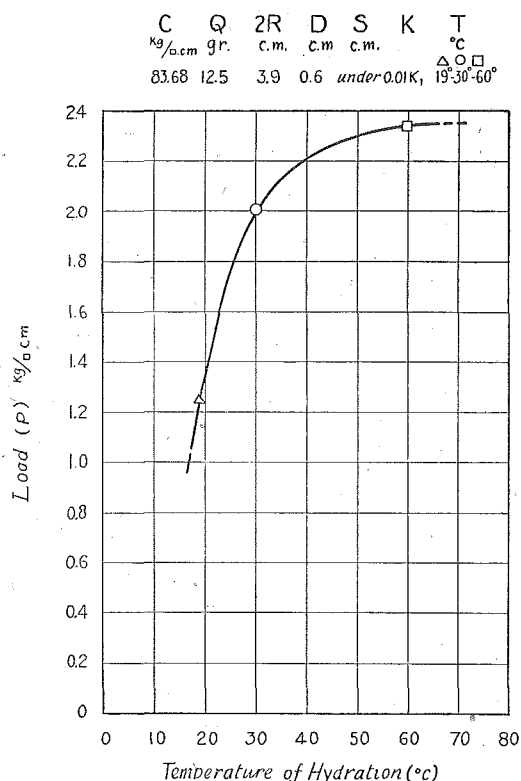


Fig. 18. Curves showing relationships between Load (P) and Temperature of Hydration.

Relation between the minimum applied load "P" by which "Hydro-expansion" is caused to begin to cease, that is, the relation between "Hydro-expansive power" " ϵ " and temperature of hydration is graphed in Fig. 19.

Fig. 18 shows that "Hydro-expansion" is effected by the temperature of hydration. At temperatures of 19°C to 30°C. "Hydro-expansive power" rapidly increases and at the higher temperatures of 30°C to 60°C, its increase becomes gradual.

(II). "Hydro-expansion" of Clay and Other Materials.

A phenomenon of "Hydro-expansion" is observed in clay but, what can be found in the other materials? For Hanaoka clay K_2 , observation has been already made in Main Test. In the present paper, the results obtained from many other materials are described.

Test Material. Materials used in this test were as follows:

Name of materials	Symbols	Specific gravity
Quartz	Q	2.336
Yubari white Shale	Y.W	2.433
Serpentine (A)	S.A	2.449
Diatom earth	D.e	2.469
Serpentine (B)	S.B	2.486
Glass Powder	G.P	2.560
Common Brick	C.B	2.565
Hanaoka Clay	H	2.570
Volcanic ash	V.a	2.577
Yubari Shale	Y.T	2.593
Tanna Clay	T	2.650
Kaolin	K	2.686
Fire Brick	F.B	2.694
Mica schist	M.S	2.694
Fushun Shale	F	2.697
Lime stone	L	2.701
Slate	S	2.740
Yubari Parting Shale	Y.S	2.874

The above materials are arranged in order of the magnitude of their specific gravity. These materials were all powdered and then used like a clay.

Test Pieces. All materials were powdered to block-size of under 0.01 cm^3 . and then applying the initial compression of $C = 40 \text{ kg/cm}^2$ test pieces of $2R = 5.6 \text{ cm.}$ and $D = 0.6 \text{ cm.}$ were made.

Dimensions and initial compression of these test pieces are the same as in No. (c) in Main Test VI.

Testing Apparatus. Large-sized "Hydro-expansion" testing machine was used.

Testing Treatment. Applying load of $P = 3 \text{ kg/24.63 cm}^2$. or $P' = 0.12 \text{ kg/cm}^2$. during hydration, expansive ratio " e " and hydrous ratio " h " were measured.

Test Results. In case of temperature of hydration $= 19^\circ\text{C}$, the results of test became as shown in Table 21.

Table 21. e and h for many Kinds of Materials.

Samples	Hydrous ratio h %	Expansive ratio e %
Q	35.47	1.14
Y.W	44.93	16.78
S.A	38.10	0
D.e	94.20	43.56
S.B	38.13	3.82
G.P	35.83	1.38
C.B	44.47	0
H	56.00	29.00
V.a	52.53	1.04
Y.T	39.93	9.26
T	38.92	10.67
K	29.93	1.11
F.B	43.40	0
M.S	32.27	1.28
F	32.27	2.50
L	32.00	2.00
S	37.93	5.00
Y.S	41.13	18.33

As known from the above table, every material absorbs water. Kaolin has the smallest hydrous ratio and Diatom earth has the largest showing respectively the values of 29.93 % and 94.20 %. Expansive ratios for Serpentine (A), Common brick and Fire brick are each zero and that for Diatom earth is the largest having the value of 43.56 %. For the complete investigation of the phenomenon of "Hydro-expansion" itself, many other materials than the above ones are furthermore to be tested. In the present paper results obtained from eighteen kinds of materials were shown for reference.

Graphically arranging the above results in order of specific gravity of their materials gives Fig. 19.

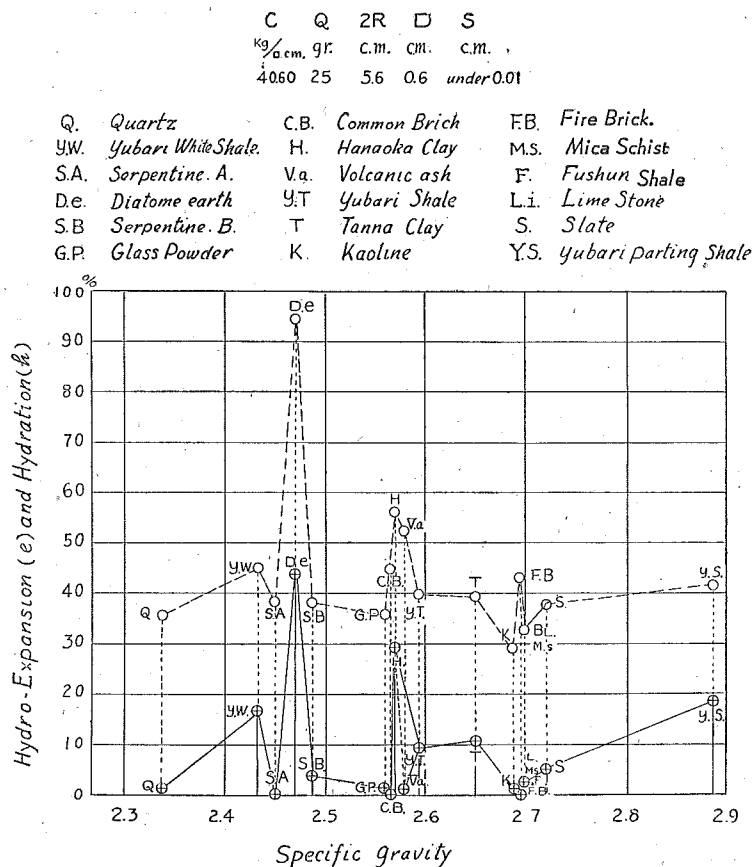


Fig. 19. Relationships between Specific Gravitay of Material and "Hydro-Expansion".

This test was not a chief object in the author's investigation but it is only one part of tests to show that when many kinds of materials are mechanically powdered smaller than a certain size, what effect the difference in materials has upon their "Hydro-expansion". As shown in this test, there is large difference in the "Hydro-expansion" of different kinds of materials and therefore "Hydro-expansion" is concerned not only with the grain size but also with various other conditions, such as surface tension of water, form of particles or chemical component and physical characteristics of the material itself etc.

Professor C.E. Terzaghi described about clay and swelling of clay in "Engineering News-Record" 1925 under the theme "Principles of Soil Mechanics" as follows:

"The term 'clay' indicates mixed-grained, plastic soils consisting of particles from 1 mm. down to 0.006 mm. in diameter and a very small percentage of 'ultra-clay' (coloidal particles in the colloid-chemical sense of the words). Hence the term includes almost all the soils which are commonly known as 'clay'."

"Swelling of Clay—If the free surface of a layer of plastic or of semi-solid clay is covered with water, the surface tension at once becomes zero and the clay expands. This swelling is identical with the expansion of the clay produced by the removal of an external load and represents elastic expansion of the clay caused by the elimination of the surface tension of the capillary water. Since the increase in bulk means increase of water content, it is apparent that water enters through the free surface and flows into the interior, impelled by the hydrostatic stress difference between the surface (where the pressure is zero, since the surface is covered with water) and the interior (where negative hydrostatic pressure exists).

If during a compression test, one drains the water completely off the surface and then removes the external load, the volume of the clay remains nevertheless unchanged, because expansion would mean increase of the moisture content and there is no free water available. On the other hand, if the volume remains unchanged, the inward pressure cannot possibly decrease; the surface tension of the capillary water takes the place of the external load. Like a rubber skin, it opposes any tendency to expansion.

Thus all phenomena associated with the cohesion of clay are capable of being explained by the single factor of surface tension. Cohesion is the internal frictional resistance produced by the capillary pressure. As the cause of the capillary pressure—the surface tension of the capillary water—is an external one, merely acting on the surface of the clay, the cohesion due to the capillary pressure may be called the 'apparent cohesion', in opposition to the 'true cohesion' produced by initial friction. As the initial friction was found to amount to not more than about 20 g./cm, the true cohesion is very small compared with the apparent cohesion".

As seen from the above description, Professor C.E. Terzaghi treated a clay as a very fine grained earthy material without touching the properties of clay itself and used a wet clay from the first. On the basis of experiment concerned with rejection of water from wet clay by compression, a discussion is made to a great extent adding the hydrostatic explanation.

In the present paper, theoretical treatment of "Hydro-expansion" was not a chief subject but the question is whether or not phenomenon of "Hydro-expansion" in experiments give a certain correct idea about the so-called "earth-pressure" exhibited in clay zone. Therefore, the author has faithfully recorded the experimental results and did not touch upon the theoretical treatment "Hydro-expansion". But, the present tests show that "*Hydro-expansion*" is to be effected by the property of material itself though grain size is uniform.

SOME EXAMPLES OF PRACTICAL APPLICATION OF TESTS.

The motive of the tests concerning "Hydro-expansion" of clay is for the examination of the so-called "earth-pressure" in clay zone encountered in Tanna Tunnel as already mentioned. Therefore, some tested results were

applied to the practice offering some reference matters for the investigation of practical problems. Some examples are as follows:

If the phenomenon of "Hydro-expansion" is considered to be concerned with "earth-pressure", it would no longer be doubted that the effect of water is a most important factor. So, one must drain off water as completely as possible.

Therefore, in actual cases drainage was taken into consideration. The thrusting power due to the above assumed hydration is enormously large as has been actually experienced in the tunnel and adit. Therefore, for the complete neutralization of this thrusting power in the Tanna tunnel, great expense was undergone and yet in vain. As bulged out quantity and speed of clay were each not every large, desisting from a direct resistance to the thrusting force and further making the section of tunnel or adit larger than necessary the usual timbering was used.

In the clearance between timbering and excavated wall cryptomeria needles were filled up as a cushion. A section whose necessary dimension was $9' \times 9'$ was enlarged to $10' \times 10'$. Then, after one year "earth pressure" began to act against the timbering having compressed the filling cryptomeria needle like a strawboard. Excavating this bulged out material and enlarging the section to the original size, the same method as the above was again applied and thereby during the next one year a state of safety was maintained. During two years, the water was completely drained off and at last a large work was successfully completed.

In the clay zone at Hanaoka Mine, compressed air was always blown into the important part for the purposes of drainage and rejection of water. Thus, clay becomes dry and hard like a concrete.

For the most parts of gallery, excavation method like that in Tanna tunnel was used with success.

However, in some galleries where the results of the author's tests were not taken into consideration, clay bulged out freely making passage impossible and at last the gallery was obliged to be abandoned.

In the above paragraphs the outline of actual examples of application of the author's tests to "earth-pressure" in clay zone at Tanna tunnel and Hanaoka mine has been briefly described but these examples are for the case where "Hydro-expansion" is suggested to be concerned with the "earth-pressure".

Regarding the magnitude of "expansive power", as it is no longer doubted that expansive power is enormously large the utilization of this natural power for mankind's use becomes worthy of notice in future.

In this paper, the results of tests are described as they stand. Hereafter, the author will extend his investigation to various problems in science and engineering. If the results of tests described in this paper become no more useful than a dead stone, yet he is satisfied with them believing that his effort was made in vain.
