SECTION II

LABORATORY INVESTIGATIONS

SUB-SECTION II a

GENERAL

EFFECT OF NATURAL HARDENING ON THE UNCONFINED COMPRESSION STRENGTH OF REMOLDED CLAYS

II a 1

(A laboratory investigation carried out at the University of Illinois, U. S. A.)

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1) PURPOSE.

In the literature of soil mechanics, much discussion has centerred on where lies the source of the strength and rigidity of undisturbed clays. Until recently, this question appeared to have only academic importance. The results of field observations carried out during the last few years have emphasized, however, that it might have very important practical implications in cases such as the consolidation of hydraulic fill dams, effect of remolding due to driving of piles, etc.

The great decrease in strength experienced by some clays when remolded at unaltered water content was first observed by the Swedish Geotechnical Commission during the investigation of landslides. Subsequently, A. Casagrande 1) observed that the consolidation characteristics of undisturbed and remolded clays were also markedly different, and he concluded that such disturbing events as the driving of piles into soft clay are likely to increase the compressibility of the clay to such an extent that the piles may actually be detrimental.

In order to explain the difference in the physical properties of undisturbed and remolded clays, Casagrande proposed a theory according to which the clay particles settle during the process of sedimentation into a definite arrangement called the "clay structure". His conception of the structure is that of a coarse-grained skeleton cemented together by highly compressed clay whose interstices are filled with soft clay. Casagrande states that "the building up of such a structure is chiefly dependent on the exceedingly slow process of natural sedimentation and consolidation" because a rapid increase of pressure during sedimentation would displace the grains before they could become bonded by highly consolidated clay. Remolding is pressumed to destroy the connecting links between the large soil grains and to replace them by the unconsolidated soft clay that fills the interstices. Since the development of the links was dependent on the exceedingly slow process of sedimentation, Casagrande was led to the conclusion that, "if we destroy the structure which nature has taken many centuries to build up, we cannot restore it".

A fundamentally different explanation of the manner in which undisturbed clays acquire their strength and rigidity has been given by K. Terzaghi 2). According to his theory, the strength and rigidity are acquired primarily by "slow physico-chemical processes" which are due to the surface activity of the mineral grains. As a consequence of its surface activity, each clay particle is surrounded by a shell of adsorbed water, almost solid near the particle, and quite viscous within a somewhat greater distance. During sedimentation, the mass of clay consolidates and the viscous layers merge. Upon further consolidation, the solid parts of the water shells may come into contact and merge at a number of points in the clay mass and, as a consequence, the mass becomes stiff. Remolding breaks the contacts between the solid water shells, displaces the grains, and introduces viscous adsorbed water between them, whereupon the clay becomes plastic.

Field evidences have been advanced in support of both conceptions 3). Since these evidences have been questioned, laboratory experiments were designed to furnish pertinent data on the subject with the purpose of throwing some light on this much discussed problem.

2. MATERIALS AND PROPERTIES.

The results on four types of clay, identified by their places of origin, are reported in this paper.

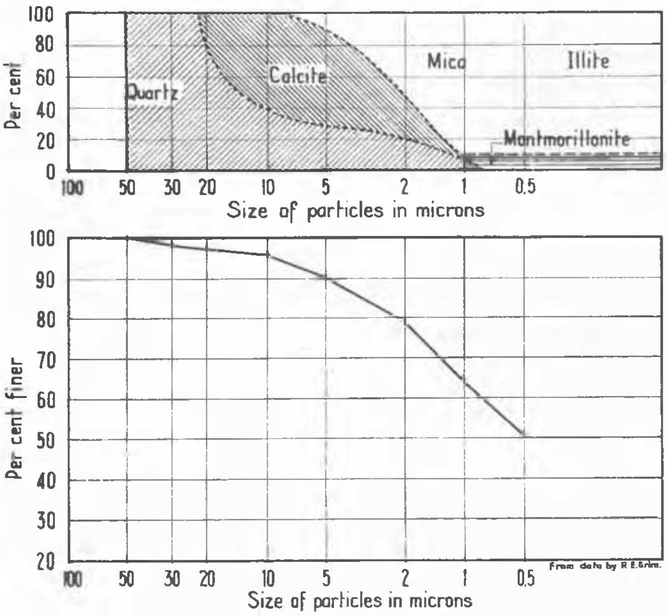
Figures 1 to 4 give the grain-size distribution and the mineralogical composition of those clays, plotted as a function of the size of the particles. The mineralogical composition was determined by the differential thermal method of studying minerals.

Table 1 gives the physical properties of the clays. The natural sensitivity indicated in column 4 denotes the ratio between the unconfined compression strength of the undisturbed material to the unconfined compression strength after remolding at constant water content.

Figure 5 shows the stress-strain relation for unconfined compression tests of the clays in the undisturbed and remolded conditions at the same water content. The natural sensitivity was derived from those tests taking as the strength of the remolded samples, and of those undisturbed that failed by bulging, the stress corresponding to 10 % strain.

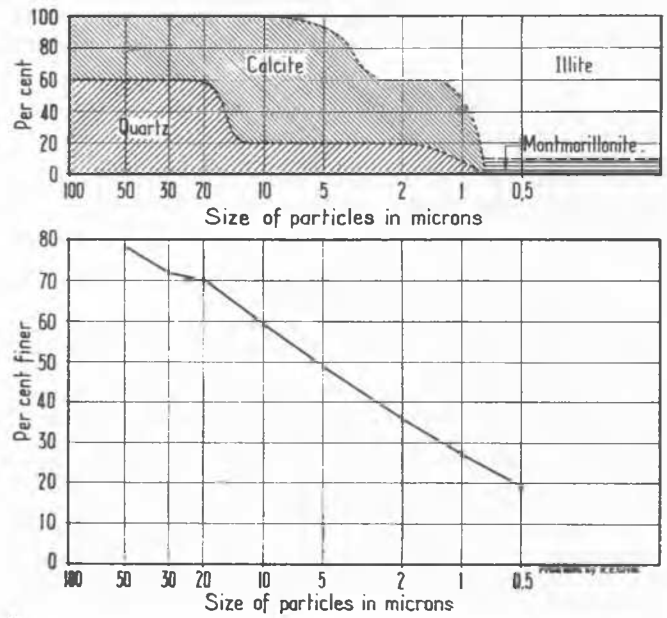
3. PROCEDURE OF TESTING.

The investigation consisted of determining the unconfined compression strength of the clays when, after complete remolding, the material had been allowed to rest at constant water content for different periods of time. Tests of this kind were made for various water contents or relative consistencies of the materials (the relative consistency = r. c. =



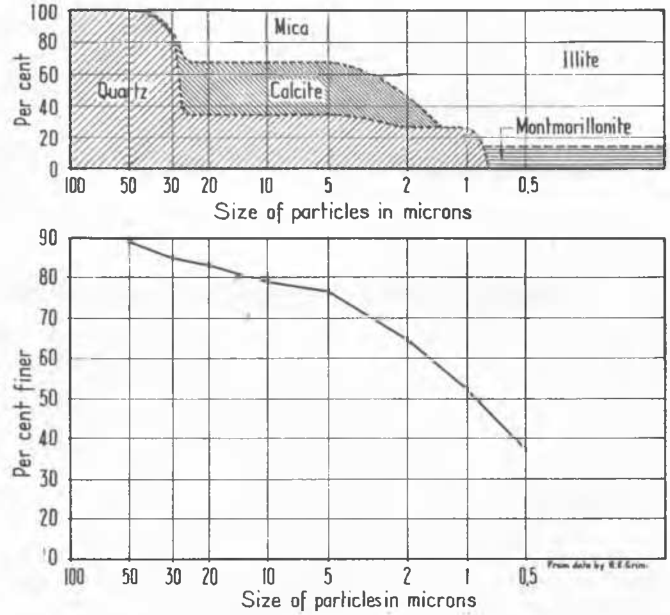
Grain-size curve and mineralogical composition of Laurentian clay.

FIG.1



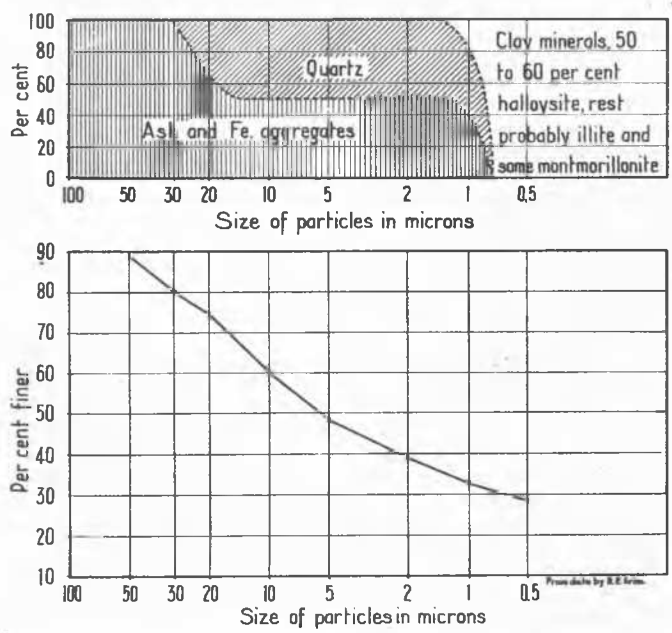
Grain-size curve and mineralogical composition of Detroit I clay.

FIG.2



Grain-size curve and mineralogical composition of Detroit II clay.

FIG. 3



Grain-size curve and mineralogical composition of Mexico clay.

FIG.4

the ratio between the water content minus the plastic limit, and the index of plasticity.).

For each type of clay enough material was mixed together to furnish a uniform mass sufficient for all the series of tests performed on it. This procedure was not followed in the case of the Laurentian clay, and as a consequence, the material employed was slightly different for the different series. The difference in the properties of the various Laurentian clay samples used was not great enough however to influence very prominently the results, and they can be compared between each other.

With each clay compression specimens were prepared in prismatic molds, Figure 6, consisting of a bottom plate of glass, two L-shaped side plates of brass, and a top plate of glass. All the plates were lined with ordinary waxed paper to avoid sticking of the clay to the mold. Later on this lining was substituted by a thin coat of mineral vaseline.

One of the specimens so made was tested immediately after it had been molded (0-day test). The rest were sealed in their molds by welding the brass and glass plates together with a fillet of paraffin, and the entire assembly placed in a tin can containing paraffin on the verge of solidifying. The tin can was later sealed full of paraffin.

The specimens stored in this manner to

TABLE 1

PHYSICAL PROPERTIES OF CLAYS						
Type of clay (1)	Specific gravity of solid matter (2)	Natural water content % (3)	Natural sensi-tivity (4)	Liquid limit % (5)	Plasticity index % (6)	Origin of clay sample (7)
Laurentian	2.67	85±	14.0±	66.0	41.0	Beauharnois, Quebec, Canada 6 to 9 ft. below ground
Detroit I	2.73	24±	2.5±	29.2	12.7	Detroit, U.S.A. 40 to 70 ft. below ground
Detroit II	2.77	47±	6.0±	51.2	26.4	Detroit, U.S.A. 25 to 40 ft. below ground
Mexico	2.69	54±	5,0±	60.8	20.4	Mexican Dam 40 ft below crest of dam

TABLE 2

UNCONFINED COMPRESSION TESTS ON LAURENTIAN CLAY. SERIES 1. (Relative consistency = 0.99)				
Tested after a resting period of (days) (1)	Water content % (2)	Ultimate strength (for 10 % strain or less) (gm/cm^2) (3)	Type of failure (4)	Acquired sensitivity (5)
0	66.7	25.7	bulge	1.0
3	66.3	49.4	shear and splitting	1.92
7	66.0	51.0	"	1.98
14	66.0	56.2	"	2.19
28	65.5	63.0	"	2.45
60	65.0	83.0	"	3.22
120	65.3	90.1	"	3.51
240	65.5	109.0	"	4.25
610	65.6	114.0	"	4.45

keep them at constant water content, were tested after periods of rest of 3, 7, 14, 28, 60, etc. days to determine the increase in strength they had experimented with respect to the specimen tested at 0 day.

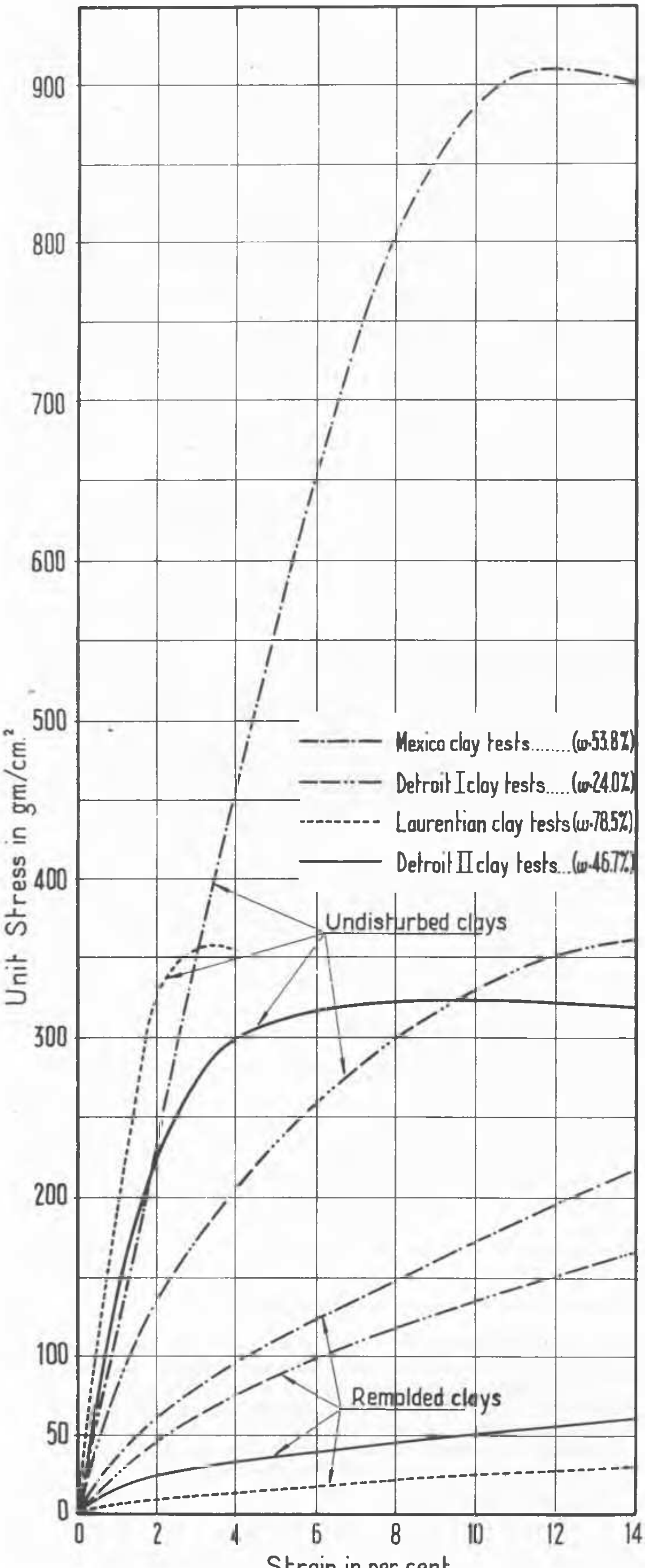
The procedure of testing gave in general good results. The tests indicate, however, a slight general trend of the moisture content of the clay to decrease with age, due mainly to absorption of water by the waxed paper. This decrease was small and did not influence practically the results.

4. RESULTS OF TESTS.

The test results are given in Tables 2 to 5 and Figures 7 to 15. The ultimate strength of the specimens that did not reach a maximum before, was taken as the stress corresponding to 10 % strain. The acquired sensitivity is the ratio between the ultimate strength of the clay after a certain period of rest and the same strength immediately after the specimens had been molded (0-day test).

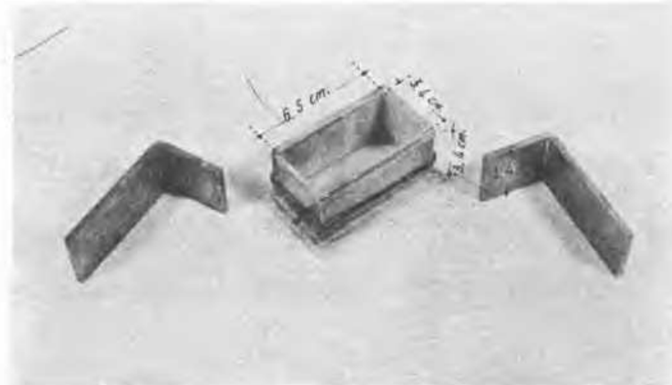
a) Laurentian clay.

The experiments on Laurentian clay comprise 7 series testing the material at different water contents. Series 1 constitutes the main series. Its results are given in Table 2, Figure 7 and Figure 8. Figure 7, that gives the stress-strain curves obtained for these tests, shows very plainly the tremendous increase on both strength and rigid-



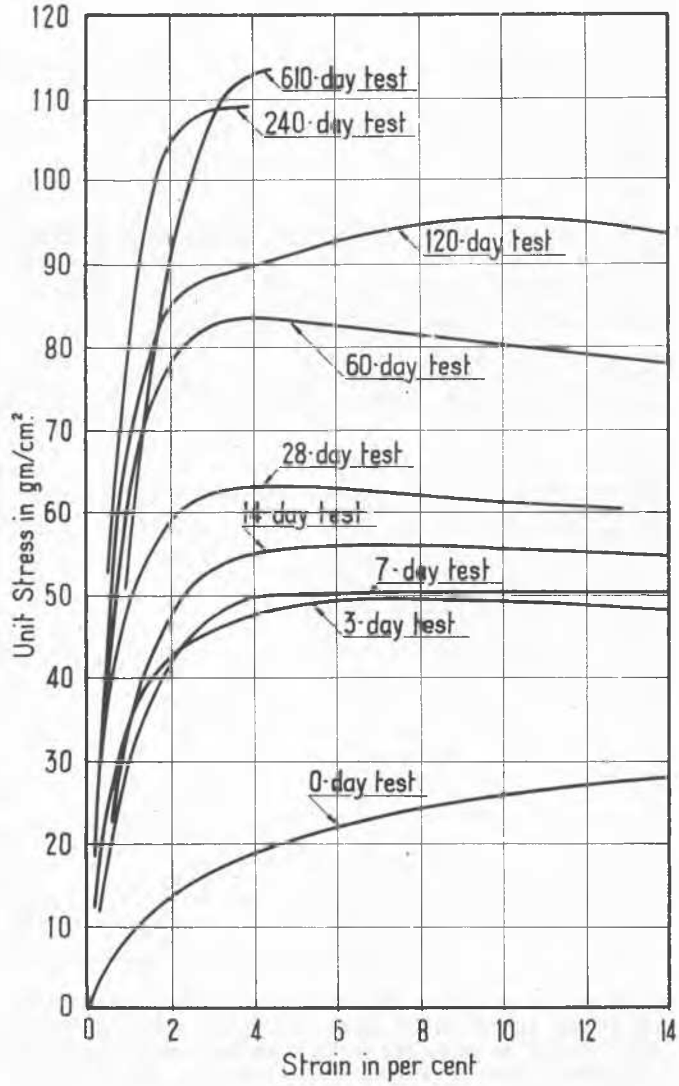
Compression tests of clays in the undisturbed and remolded state at natural water content.

FIG. 5



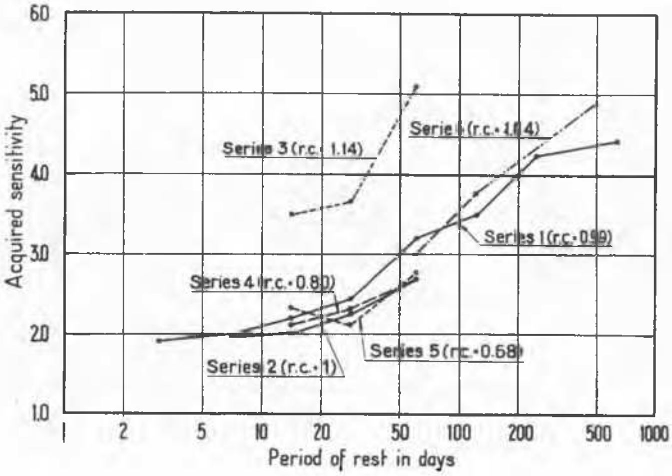
Molds for compression tests

FIG. 6



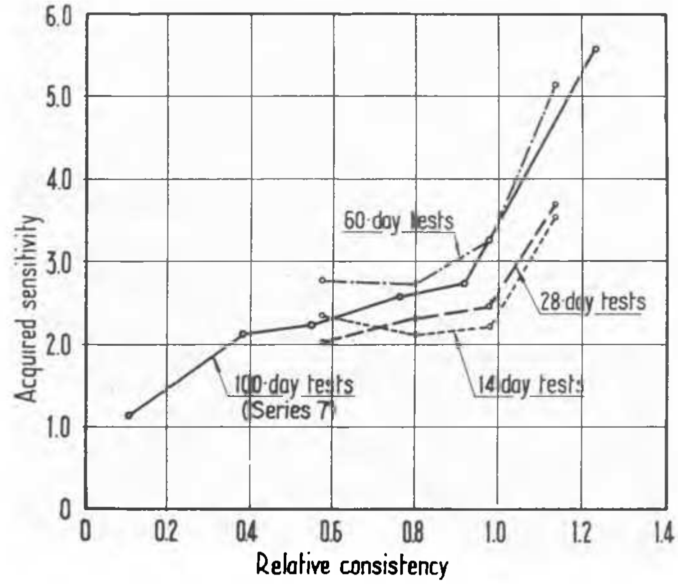
Laurentian clay tests.

FIG. 7



Acquired sensitivity as a function of the period of rest-Laurentian clay tests.

FIG. 8



Relation between relative consistency and acquired sensitivity-Laurentian clay tests.

FIG. 9

ity that the clay experimented, from the very beginning, when it was simply allowed to rest at constant water content. The sensitivity acquired after 610 days of rest reached a value of 4.45, nearly one third of the natural sensitivity of the undisturbed material as given in Table 1.

The results of Series 2 to 6 are given in Figure 8 and they indicate increases in strength similar to those recorded in Series 1. Series 7 was undertaken to determine the relation between the increase in strength and the relative consistency, after a fixed period of rest. Its results are given in Figure 9, where are also included results deducted from the other series. For Series 7, the 0-day strength was obtained after testing the specimen that had tested, by remolding it at constant water content and testing it again. In this way, the influence of the small loss in moisture experimented with time by the specimens of the other series was entirely eliminated.

All the curves of Figure 9 indicate that, for a given period of rest, the relative increase in strength increases with the relative consistency of the clay. In other words, in the range of consistencies tested, the rate of hardening increases with the water content. This phenomenon may partly explain the reason for the high natural water content of the Laurentian clay, which was higher than any of those tested. If under the slow process of sedimentation and subsequent consolidation by which the clay strata was formed, hardening could have taken place in a manner similar to that in the test specimens, the clay would have tended to stabilize itself at a critical water content for which the rate of hardening is the greatest. This critical water content is evidently higher than any used in this investigation, but the natural water content of the clay is also higher.

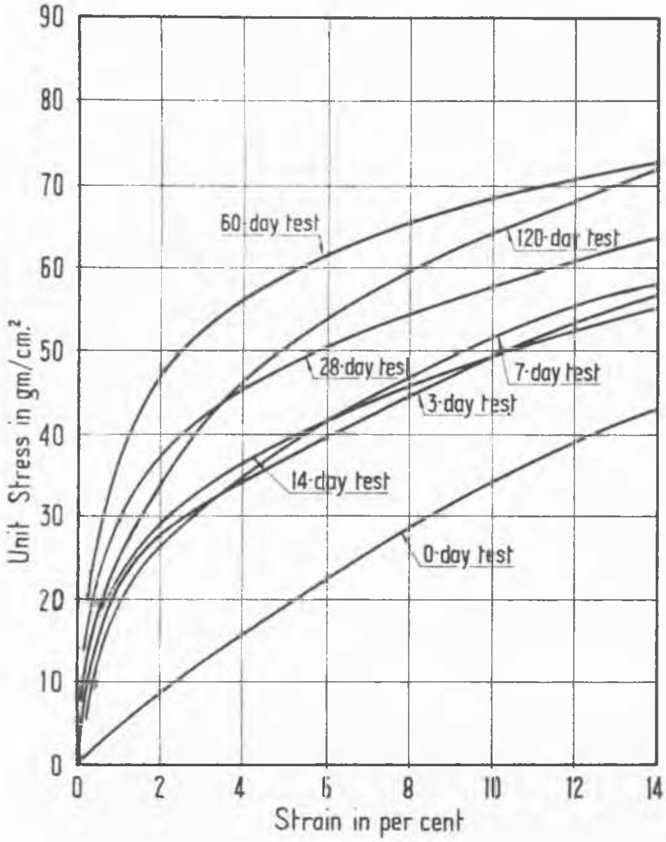
b) Detroit I clay.

Tests on Detroit I clay comprise four groups designated as Series a to d. The results are given in Table 3 and Figures 10 to 12. Table 3 and Figure 10 give the results of

TABLE 3

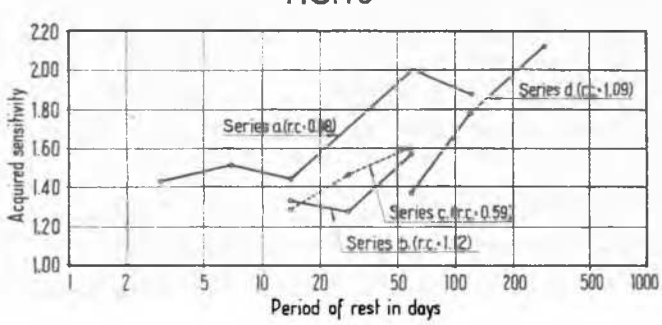
UNCONFINED COMPRESSION TESTS ON DETROIT I CLAY. SERIES a.
(Relative consistency = 0.98)

Tested after a resting period of (days) (1)	Water content % (2)	Ultimate strength (for 10 % strain or less) (gm/cm^2) (3)	Type of failure (4)	Acquired sensitivity (5)
0	29.1	34.2	bulge	1.0
3	29.1	49.0	"	1.43
7	29.0	51.5	"	1.51
14	28.9	49.4	"	1.44
28	28.9	58.0	"	1.70
60	28.3	68.6	"	2.00
120	28.6	64.2	"	1.88



Detroit I clay tests.

FIG.10



Acquired sensitivity as a function of the period of rest-Detroit I clay tests.

FIG.11

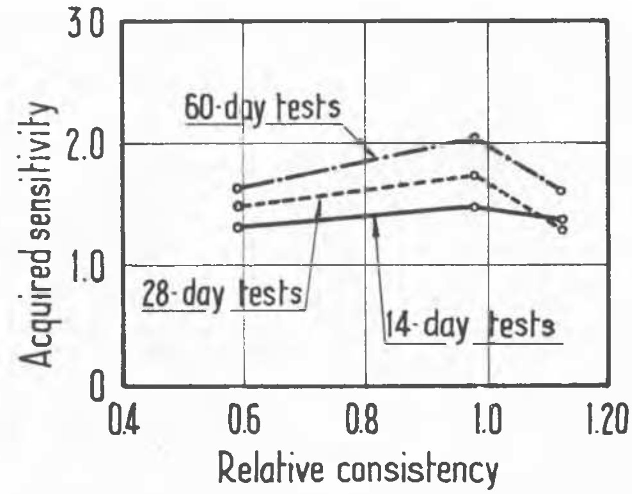
Series a that was the main series of tests on this clay.

The maximum acquired sensitivity measured in these series of tests reached a value a little over 2.10, which compared with the natural sensitivity of about 2.5 of Table 1, indicates that this clay may regain with time a very great part of its original strength lost by remolding.

The results given in Figure 12 are not extensive enough to permit a definite conclusion, but they seem to indicate that this clay has its maximum rate of hardening for a water content near the liquid limit. The water content of the clay in the ground is smaller than this value.

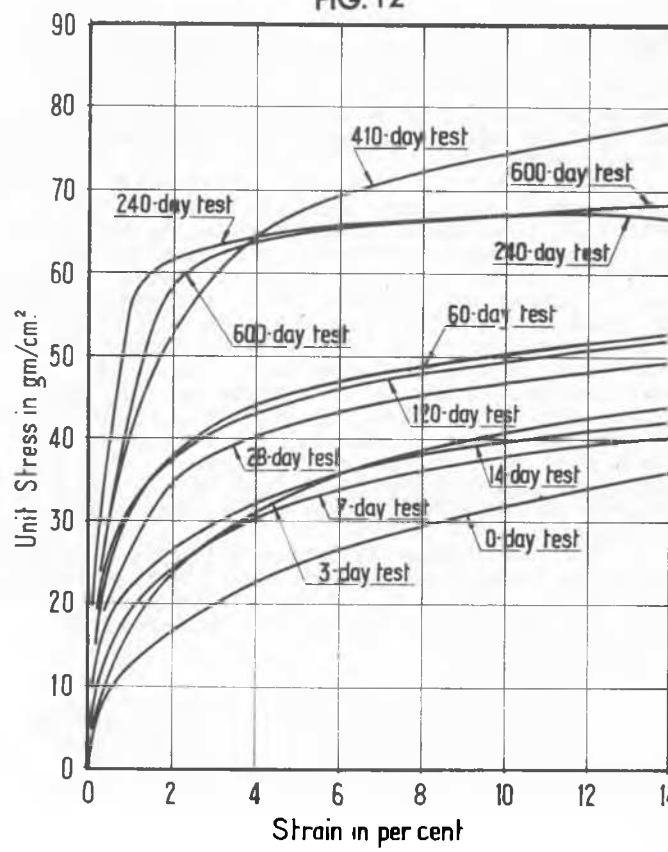
c) Detroit II clay.

Only one series of tests was made on this clay, at a relative consistency a little higher than that corresponding to the natural water content of the clay in the ground.



Relation between relative consistency and acquired sensitivity Detroit I clay tests.

FIG. 12



Detroit II clay tests.

FIG. 13

The results are given in Table 4 and Figures 13 and 14.

The rate of increase on strength and rigidity was for this clay comparatively slower than for the other two types of clay already reported. Only after 240 days of rest the stress-strain curve acquired a shape similar to that of the undisturbed material. The acquired sensitivity reached, however, values up to 2.36, about one third of the natural sensitivity of the undisturbed material.

d) Mexico clay.

Tests on this clay include only a short series whose results are given in Table 5 and Figure 15. The increase in strength experi-

TABLE 4

UNCONFINED COMPRESSION TESTS ON DETROIT II CLAY.
(Relative consistency = 0.94)

Tested after a resting period of (days) (1)	Water content % (2)	Ultimate strength (for 10 % strain or less) (gm/cm^2) (3)	Type of failure (4)	Acquired sensitivity (5)
0	50.7	31.6	bulge	1.0
3	49.3	40.6	"	1.29
7	48.9	37.7	bulge and splitting	1.19
14	50.2	39.6	bulge shear and splitting	1.25
28	49.8	46.7	"	1.48
60	49.6	50.2	bulge and shear	1.59
120	50.3	49.4	"	1.56
240	49.9	67.0	"	2.12
410	50.1	74.5	"	2.36
600	48.9	67.2	shear	2.13

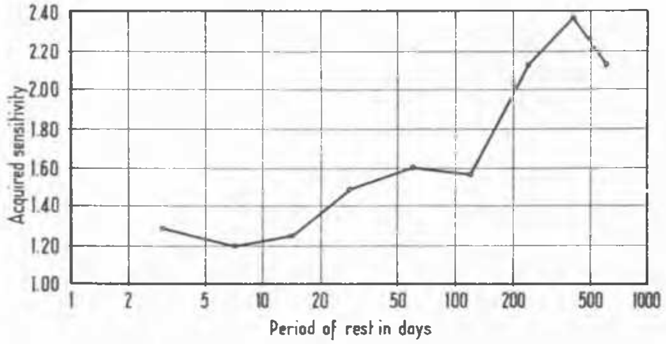
TABLE 5

UNCONFINED COMPRESSION TESTS ON MEXICO CLAY
(Relative consistency = 1.03)

Tested after a resting period of (days) (1)	Water content % (2)	Ultimate strength (for 10 % strain or less) (gm/cm^2) (3)	Type of failure (4)	Acquired sensitivity (5)
0	61.5	44.4	bulge	1.0
14	----	58.5	"	1.32
28	----	55.7	bulge and shear	1.25
60	----	61.8	"	1.39

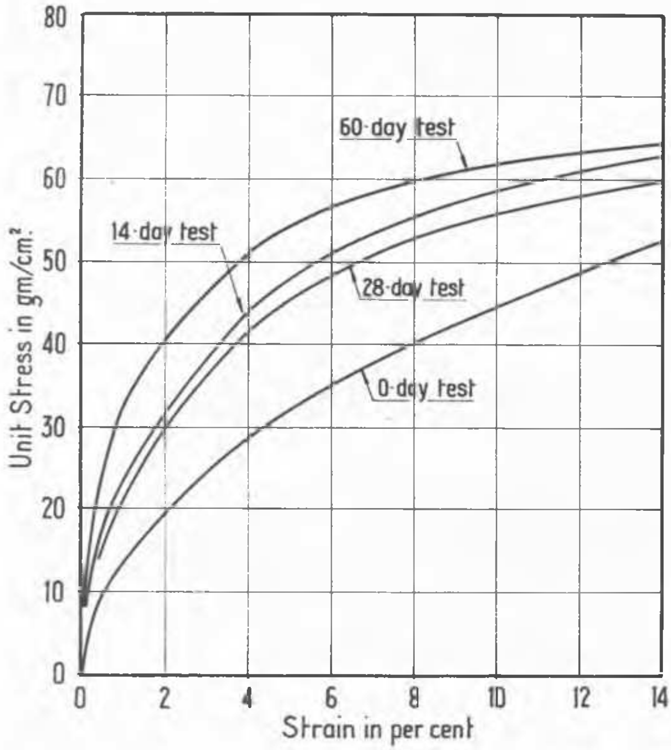
mented by the material during the 60-day extension of this series was small when compared with the natural sensitivity of the clay. These results were rather disappointing because the clay came from the core of a hydraulic fill dam constructed many years ago, where a recent investigation showed that the consolidation of the clay core did not proceed as would have been expected from existing theories. The water content of the core, more than 30 years after construction,remained practically independent of the depth below the crest at a value close to the liquid limit. Yet, the unconfined compressive strength was found to increase with depth and the strength of the material near the base of the core at a depth of 80 ft. was nearly three times as great as the strength of the material in the upper part.

It is believed that the increase in strength experimented by the remolded clays when kept at constant water content may partly explain that phenomenon. The results of this series of tests do not warrant completely this ascertion. The series of tests run is not extensive enough, however, to draw any conclusion. Besides, the tests on Detroit II clay indicate that if allowed to rest longer, the Mexico clay might still experiment considerable increases in its strength and rigidity, should it behave as the above mentioned material.



Acquired sensitivity as a function of the period of rest-Detroit II clay tests.

FIG.14



Mexico clay tests.

FIG.15

5. DISCUSSION AND CONCLUSIONS.

The results of the tests indicate that, if a clay that has lost a great part of its original unconfined compressive strength by a process of complete remolding, is later kept for a certain period of time at constant water content, the clay regains a sensible part of its lost strength. Depending on the type of clay, this phenomenon may, in some cases, restore the greatest part of the original strength of the undisturbed material. This fact is in complete contradiction with the theory that assigned most of the difference in strength between undisturbed and remolded clays to a structure that being destroyed could never be recovered.

Since the clays did not have an opportunity to build up any kind of a structure, it must be admitted in order to explain the results, that the period of rest permitted the clay to restore or improve the contacts among the shells of adsorbed water surrounding each particle, that were disturbed by remolding. This explanation is in agreement with Terzaghi's concept of the cause of the strength and rigidity of undisturbed clays, referred to in Part 1. The results, however, do not warrant completely this concept. It is believed that in the affirmative case, the thixotropic phenomena studied in this investigation should have, on the basis of the above hypothesis, restored practically all of the original strength of the undisturbed clay. This was nearly so in the case of the Detroit I clay, but not so for the other materials tested. It remains no doubt, however, that the tests results appear to indicate that a sensible part of the strength and rigidity of undisturbed clays depend on the physico-chemical processes resulting from the surface activity of the mineral grains.

The most important practical conclusions to be deducted from this investigation are as follows:

a) The natural sensitivity may be a controlling clay property in some problems of soil mechanics such as landslides. It may not be of such significance in problems of foundation engineering where the critical period of behavior of the clay occurs some time after remolding has taken place. Since some clays may recover a sensible part of their strength in a relatively short time after remolding, the natural sensitivity may be no indication of the behavior of the soil.

b) In all cases in which the method of construction involves remolding of clay material, such as driving of piles in or through clay strata, the importance of remolding may be much less than what Casagrande's concept of the clay structure would suggest.

6. ACKNOWLEDGEMENT.

Thanks are due to Dr . K. Terzaghi and R.B. Peck for continued guidance throughout this investigation.

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1) A. Casagrande, "The Structure of Clay and its Importance in Foundation Engineering", Journal of the Boston Society of Civil Engineers, April, 1932.

2) K. Terzaghi, "Undisturbed Clay Samples and Undisturbed Clays", Journal of the Boston Society of Civil Engineers, July 1941.

3) See also discussion of "Application of Soil Mechanics in Designing Building Foundations" by A. Casagrande and R.E. Fadum, Trans. A. S. C. E., 1944.

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