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NOT TO BE TAKEN FROM THIS ROOM

THE STABILIZATION WITH CEMENT

OF A TYPICAL BOSPORUS CLAY

by

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B.S. in C.E. Robert College, 1969

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in
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INTRODUCTION

This study was conducted to evaluate the effects of curing time (age), water content, density and temperature on the compacted soil-cement mixtures, and variation of consistency indices of soil with different cement contents by using a chosen Bosphorus clay.

For this purpose, unconfined compression tests and repetition-al wetting-drying and freezing-thawing tests were performed. Variation of unconfined compressive strength with age, cement content, temperature, density and water content were studied and plotted to evaluate the results. Collected data at the end of the repetitional freezing-thawing and wetting-drying tests were used to evaluate volume and moisture changes and soil-cement losses during the test.

A total of 198 samples were tested for compressive strength to evaluate the effect of age, density, temperature and water content. And 40 samples were used for wetting-drying and freezing-thawing tests for the evaluation of volume and moisture changes together with the soil-cement losses.

While compacting samples at optimum water content for maximum dry density, a deviation of one per cent in optimum water content and two per cent in dry density were considered acceptable, and testing was continued. The "Speedy Moisture Tester" was used throughout testing to check the moisture determinations.

In conducting this study, the earlier researchers and their accomplishments were taken into consideration, too. Because of the

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increasing importance of soil-cement in recent years, much research has been conducted on the subject. Among these the works of Miles D. Catton, L.T.Norling, H.F.Winterkorn, E.J.Felt, R.G.Packard, G.A.Chapman, A.Herzog and J.K.Mitchell are worth mentioning.

Also, an attempt was made to explain the nature and mechanism of soil-cement stabilization by analysing recent research conducted on the subject.

THE HISTORY OF THE CEMENT STABILIZATION

The origin of the idea of mixing soil and cement to produce a new material of known characteristics has not been definitely founded.

In 1917, J.H.Amies (U.S.A.) was issued a patent "soilamies" on soil and cement mixtures for highway use. Three years after this, another patent was issued for "soilcrete" again for highway use. But until 1932, the properties of this new material obtained by mixing soil and cement was not clearly known.

The investigation in 1932 started under the leadership of Dr. C.H.Moorefield from the South Carolina State Highway Department.

The predominant influence of the surface chemistry of soils was first encountered in 1936 on a field project of the Wisconsin State Highway Department.

The road performance of the trial projects in 1933 and 1934 revealed the soil and cement as compatible materials. Because of this reason they could be used (mixed) to form a usable road.

As a result of these experiences, the Portland Cement Association established a fellowship at the University of Missouri under the direction of Prof. Hans F.Winterkorn (M.ASCE) to explore the effect of surface chemistry. One of the main objectives of the Portland Cement Association was to produce a low-cost construction material that could be used for highway traffic paving.

While the literature research was continued by considering many hypotheses, R.R.Proctor (M.ASCE) of the Los Angeles, California

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Water Board came up with his famous moisture-density relations.

The Portland Cement Association, keeping in mind that compacting soil to maximum density at optimum moisture content resulted optimum load carrying capacity and optimum structural strength, started its investigations. Research and testing programs were developed for the evaluation of compacted soil-cement mixtures.

Many factors governing the test such as temperature, the number of cycles of testing samples, duration, moisture content, soil gradation, surface area, compressive strength densities and cement contents were considered in studying 329 soils.

The cooperative studies and investigations of American Society for Testing Materials, the U.S.Bureau of Public Roads and some universities resulted first A.S.T.M. tentative test procedures for determining the moisture-density relations of soils under the Chairmanship of Miles D.Catton (M.ASCE) in 1942.(1)

After this time, several million square meters of soil-cement roads have been constructed until today.

1. Assistant to Vice President Research and Development, Portland Cement Association, Chicago, III.

I. - THEORY

A. Definition of Soil-Cement And Its Requirements

Soil-cement is a low-cost construction material in lightweight traffic paving having its unique properties. It is defined by Miles D. Catton as "a tightly compacted mixture of pulverized soil, Portland cement and water which, as the cement hydrates, forms a hard, durable structural material." ²

One of the general requirements for soil-cement is that 55 per cent or more of the soil must pass a No.4 sieve. Therefore soil-cement primarily is related to naturally occurring fine grained soils, with the consideration of soil as an aggregate in the soil-cement mix.

B. Research Concerning Soil-Cement

Research concerning soil-cement started mainly to find a low-cost but at the same time durable construction material for paving. As a result of extensive research program by the Portland Cement Association in 1945, some dependable methods were developed for testing the quality of soil-cement mixtures.

-
2. Catton, Miles D., "Early Soil-Cement Research And Development," American Society of Civil Engineers, Journal of the Highway Division, vol.85, part 1, p.2 .

1. Development of Standard Tests

L.T.Norling expresses the need for the development of standard tests as follows:

"... The next step in the 1935 research program was to devise methods of measuring the effect that various cement contents, moisture contents and densities have on the physical properties of compacted soil-cement mixtures. Since the rate and amount of cement hydration would influence the final results materially, specimens were permitted to remain undisturbed for 7 days in an atmosphere of high humidity before being tested. This permitted hydration of significant portion of the cement.

"... Thus, the wet-dry and freeze-thaw tests were evolved to reproduce in the laboratory the phenomenon of moisture changes in soils..."

Therefore he states that,

- "(a) the wet-dry test was designed primarily to simulate shrinkage forces...
- (b) the freeze-thaw test was designed to simulate internal expansive forces produced by moisture changes in the fine-grained soils."

There are some moisture changes in specimens. These moisture changes result in volume changes. The main function of the wet-dry and freeze-thaw tests are to determine the minimum cement contents that will resist these volume changes.

2. Testing Criteria Concerning Soil-Cement

Later, some testing criteria were developed by researchers in applying the wet-dry and freeze-thaw tests. These criteria were about:

3. Norling, L.T., "Standard Laboratory Tests For Soil-Cement Development, Purpose And History of Use," Highway Research Record, 1963, No. 36, p.2.

- (a) volume changes;
- (b) maximum moisture content;
- (c) soil-cement losses;
- (d) trend of compressive strength.

These criteria are given by Miles D. Catton as follows:

- "(a) Maximum volume at any time during either wet-dry test or freeze-thaw test shall not exceed volume at time of molding by more than 2 per cent.
- (b) Maximum moisture content at any time during either wet-dry test or freeze-thaw test shall not exceed that quantity which will completely fill the voids of specimen at time of molding.
- (c) Soil-cement losses during 12 cycles of either wet-dry or freeze-thaw test shall conform to the following standards: (4)
 Soil groups A-1-a, A-1-b, A-3, A-2-4 and A-2-5, not over 14 per cent
 Soil groups A-2-6, A-2-7, A-4 and A-5, not over 10 per cent
 Soil groups A-6, A-7-5 and A-7-6, not over 7 per cent.
- (d) Compressive strengths of soil-cement test specimens, soaked in water 1 to 4 hours prior to test shall increase with age and with increases in the ranges of cement content producing results meeting requirements a, b, and c." 5

3. Reasons to Select These Criteria

L.T. Norling expresses the reasons to select these criteria in the following manner:

- "(1) The criterion of maximum volume increase of the specimens (not more than 2 per cent) was chosen as an indication that the cement is holding the mass intact.

4. U.S. Bureau of Public Roads Classification.

5. op. cit., in 2, pp.1-7.

- (2) The criterion of maximum moisture content (not more than that required to fill the voids) was selected as a further indication of resistance to disruptive volume changes.
- (3) The criterion of maximum soil-cement loss from brushing was used as an indication that the forces of expansion and shrinkage resulting from the wetting and drying and freezing and thawing, that will disrupt and disintegrate soil specimens, had been resisted.
- (4) The compressive strength criterion was used because increases in strength due to increases in time and cement content are evidence that the cement is functioning normally and that the soil is not interfering with hydration of the cement." 6

C. Factors Affecting Soil-Cement

Soil-cement is the name given to the mixture of natural soil and Portland cement with water. It forms a hard, durable and structural material as the cement hydrates. The strength and durability of soil-cement are dependent on several factors. These factors can be summarized as follows:

(A) The nature of the soil

- (a) The type and structure of the soil;
- (b) the specific surface of the soil;
- (c) the exchangeable ions that soil carries;
- (d) organic matters in the soil;
- (e) the gradation of the soil;
- (f) the affinity of soil for water.

6. op.cit., in 3, p.3 .

(B) The amount and type of cement

- (a) Normal Portland cement;
- (b) high-early Portland cement;
- (c) Cement content. *

(C) Duration of mixing

- (a) Continuous mixing;
- (b) mixing after cement hydration.

(D) Compaction conditions

- (a) Effect of water content; *
- (b) effect of compacted density. *

(E) Age and curing

- (a) Curing temperature; *
- (b) the length of curing time; *
- (c) relative humidity.

(F) Admixtures

- (a) Amount of admixture;
- (b) type of admixture. 7

7. Among the factors mentioned above, which affect the properties and behaviour of soil-cement, those marked with a star are studied for this paper.

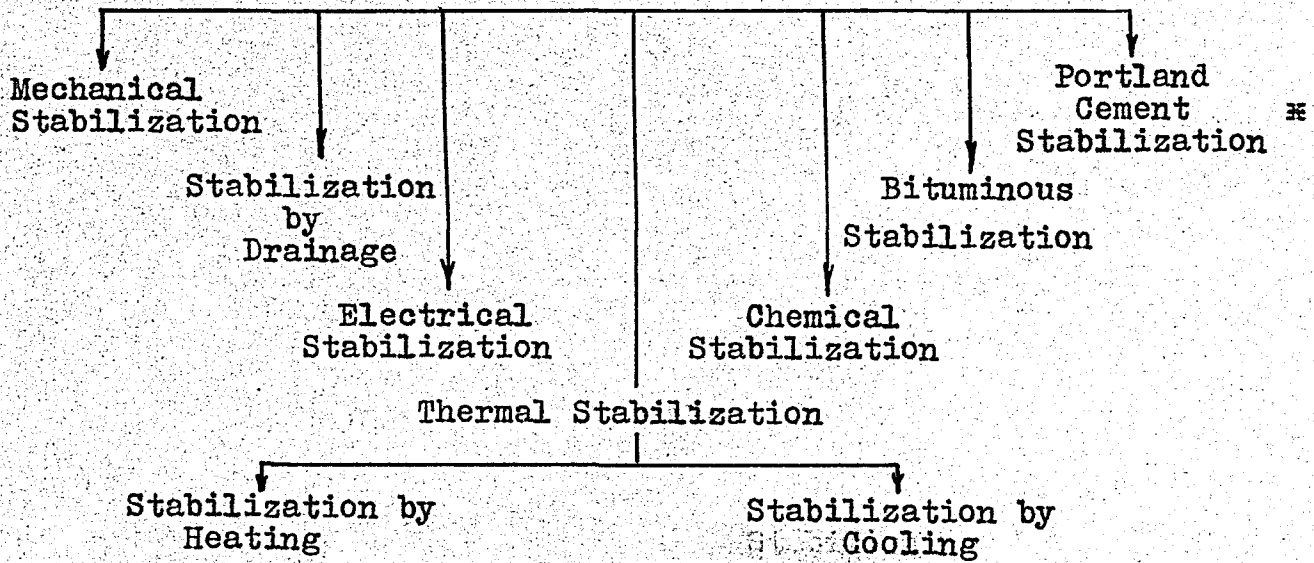
D. Soil Stabilization

1. Definition

"Soil stabilization is any physical, chemical or other method employed for the purpose of improving soils in order to make them serve better for the intended engineering usage."⁸ Therefore engineering performance of soil is improved by altering any property of a soil. This alteration can be done in many ways. The table below summarizes the main stabilization methods:

2. Different methods

The Methods of Soil Stabilization



≡ This is the method used in this study.

8. Winterkorn, Hans F., "Soil Stabilization," Proceedings of the Second International Conference On Soil Mechanics and Foundation Engineering, Rotterdam, 1948, p.209.

3. Composition And Hydration Reactions of Portland Cement ⁹

Composition:

Portland Cement is obtained by burning calcareous and argillaceous materials, or other silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3) bearing materials at a high temperature.

A small amount of gypsum (2 to 4 per cent), or hydrated calcium sulphate ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is usually added to the clinker before grinding. Therefore the composition of Portland cement is made up of calcium oxide, silica, alumina, iron oxides, magnesium oxide and sulphur trioxide. But these oxide constituents exist in Portland cement mainly as calcium silicates and aluminates as follows:

Tricalcium silicate ($3\text{CaO} \cdot \text{SiO}_2$)

Dicalcium silicate ($2\text{CaO} \cdot \text{SiO}_2$)

Tricalcium aluminate ($3\text{CaO} \cdot \text{Al}_2\text{O}_3$)

Tetracalcium aluminoferrite ($4\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3$) .

Using the nomenclature in cement chemistry, these were expressed as:

C_3S

where: $\text{C} = \text{CaO}$

C_2S

$\text{S} = \text{SiO}_2$

C_3A

$\text{A} = \text{Al}_2\text{O}_3$

C_4AF

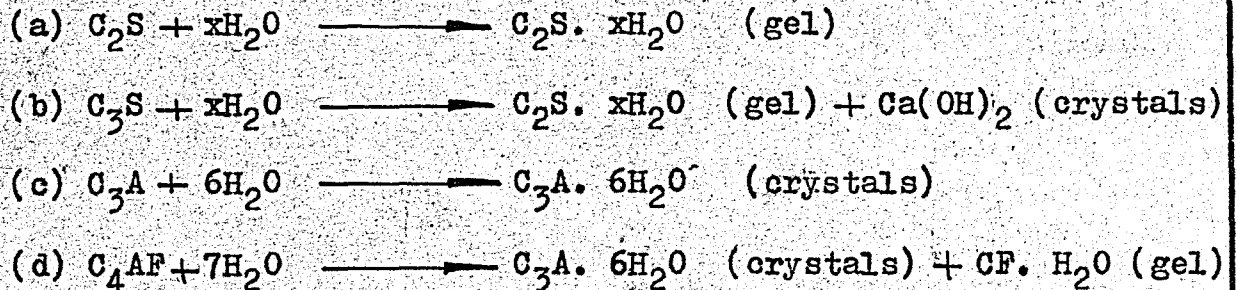
$\text{F} = \text{Fe}_2\text{O}_3$

In addition to those above, there may be free magnesium oxide (MgO) and calcium oxide (CaO) as in the sample used in this study.

9. Jastrzebski, Zbigniew D., Nature And Properties of Engineering Materials, 1959, pp.492-500.

Hydration Reactions of Cement:

When the cement is mixed with water to a paste, hydration reaction begins. At the end of these reactions, a gel is formed as well as crystalline products. These reactions are given as follows:



4. The Mechanism of Soil-Cement Stabilization ¹⁰

Because of the improvement in the engineering properties of soils in recent years when treated with cement, the attention was drawn to explaining the nature of soil-cement reactions accompanying soil stabilization. There are two views to be considered about the reactions of soil-cement, as given by A. Herzog and J.K. Mitchell.

- (1) Hardening of soil-cement is only due to the hydration of cement.
- (2) There are reactions taking place between the hydrating cement and clay components, in addition to the hydration of cement.

In the first case, soil is considered to be a chemically inert component.

10. Herzog, A., J.K. Mitchell, "Reactions Accompanying Stabilization of Clay With Cement," Highway Research Record, 1963, NO.36, pp. 146-172.

(a) Adjacent soil grains are bound together by cement particles.

A skeleton of hard, strong and unaltered soil results from this.

(b) Since the cement particles fill the voids, permeability and swelling of soil decreases. Therefore the resistance of soil-cement to moisture changes increases.

In the second case,

(a) Additional cementitious material is produced. Therefore the bonds between the soil grains themselves and between soil and cement particles are strengthened.

(b) In this case, the plasticity of clay decreases and thus soil becomes less expansive when exposed to water.

A. Herzog and J.K. Mitchell divide the reactions accompanying stabilization of clay with cement into two parts:

(1) Primary reactions

(2) Secondary reactions.

The primary reactions constitute hydrolysis and hydration of cement with the usual cement hydration products, the liberation of fresh calcium hydroxide Ca(OH)_2 , and the increase of PH.

The secondary reactions constitute the attack of clay particles because of the high PH and Ca(OH)_2 concentration, the breakdown of amorphous silica and alumina caused by the high PH and Ca(OH)_2 concentration, and combination of dissolved amorphous silica and alumina with calcium ions which precipitate to form secondary cementitious materials.

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A.Herzog and J.K.Mitchell state that when lime is produced at the end of the first primary reaction, interaction of lime and clay minerals influence the soil-cement stabilization.

Herrin and Mitchell divide the reactions taking place between clay minerals and lime into two types.¹¹

- (1) Rapid reactions: (a) ion exchange;
 (b) flocculation.
- (2) Slow reactions: (a) carbonation;
 (b) pozzolanic reactions;
 (c) formation of new materials.

When lime is added, the electrolyte content of pore water increases and this leads to the result of ion exchange by the clay to calcium form. And since the clay components possess pozzolanic properties, slow reactions also take place. Since dissociation of Ca(OH)_2 increases the PH of molding water, the reactivity of surface silica and alumina increase, too. "Therefore the calcium ions combine with the reactive hydrous silica and alumina and form gradually hardening cementitious material..."¹²

From the above discussions, the following statements may be drawn for the possible mechanism of soil-cement stabilization:

11. Herrin, M., H.Mitchell, "Lime-Soil Mixtures," Highway Research Board Bulletin, 1961, No. 304, pp.99-138.

12. op.cit., in 10, pp.148-149.

- (a) Cement hydrates and releases lime Ca(OH)_2 , calcium silicate hydrates, and hydrated aluminates.
- (b) The lime increases the PH of the molding water and flocculation starts, and clay is converted to calcium form by Ca^{++} ions.
- (c) Silica (SiO_2) and alumina (Al_2O_3) are dissolved from clay minerals by Ca(OH)_2 . When Ca(OH)_2 is mixed with clay minerals, flocculation and ion exchange starts, and cementitious materials are produced as a result of rapid and slow (puzzolan-type) reactions.
- (d) Gaining strength of soil-cement results from the flocculation of clay particles.

II. MATERIALS AND APPARATUS

A.. Materials

1. Soil

(a) Properties of Soil Used. The clay soil (TOPSER-RED) used for this study was obtained from an excavation near TOPSER Brick Factory at Büyükdere, at a depth of about five or six meters below the existing ground level.

Some of the properties were examined to a great extend at the İstanbul Technical University. The reddish brown, low plasticity soil had the following properties as referred to in an investigation conducted by Professor Vahit Kumbasar and Doçent Dr. Ergün Toğrol from the İstanbul Technical University.

Liquid Limit (w_L)	=	38.1 %	38.0 %	(13)
Plastic Limit (w_p)	=	22.3 %	22.8 %	
Plasticity Index (I_p)	=	15.8 %	15.2 %	
Unit Weight (gr/cm^3)	=	2.81		

Granulometry

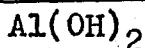
Sand	=	34 %
Silt	=	36 %
Clay	=	30 %
Activity	=	0.53

The soil was classified according to AASHO classification system as A-6.

13. These are the results of the tests conducted in the Laboratory.

(b) Composition of This Soil. The main clay mineral constituting the structure of TOPSER-RED is kaolinite with the formula $(Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O)$. The structure of the crystal consists of alternate layers of silica (SiO_2) and gibbsite ($Al(OH)_2$). Typical kaolinite minerals are from 0.1 to 10 microns in diameter, and have a diameter to thickness ratio of the order of 40:1 or 50:1.¹⁴

Gibbsite



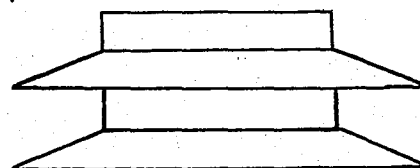
Silica



(a) BUILDING BLOCKS

(b) STRUCTURAL UNIT

+ 0.1 to 10 microns +



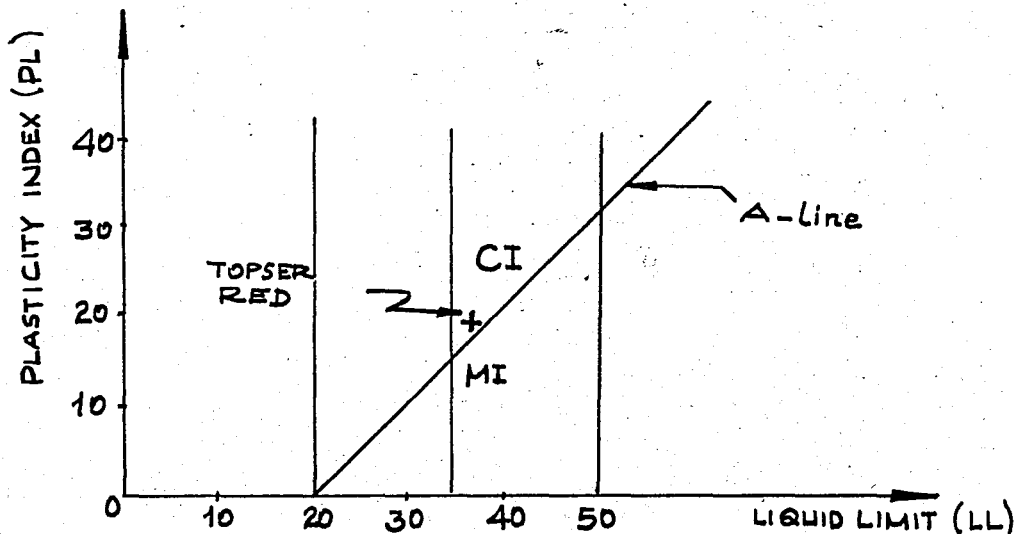
(c) KAOLIN PARTICLES

The soil has been classified according to the U.S. Bureau of Public Roads' triangular classification system, and it is found to be a "silty clay."

The position of the soil is shown in the "Casagrande Plasticity Chart" on the next page. As it may be observed from the chart, the place of this particular soil used is ⁱⁿ a transitional region between MI and CI.

14. Scott, Ronald F., Jack J. Schoustra, Soil Mechanics And Engineering, New York, 1968, pp.20-21.

The Position of TOPSER-RED In Casagrande Plasticity Chart



The properties of CI and MI in the Casagrande classification system are given as: fine grained soils having medium plasticity, and with liquid limits between 35 and 50. They can be readily rolled into threads when moist. Their value as a road foundation when they are not subject to frost action is fair to poor. Shrinkage or swelling properties of these soils are medium to high. Then the drainage characteristics are fair to impervious.

The activity diagram of TOPSER-RED is shown on the next page. The activity is defined here as the ratio of the plasticity index of a soil to its clay content. The TOPSER-RED has the following consistency indices and clay content:

$$LL = 38.1 \%$$

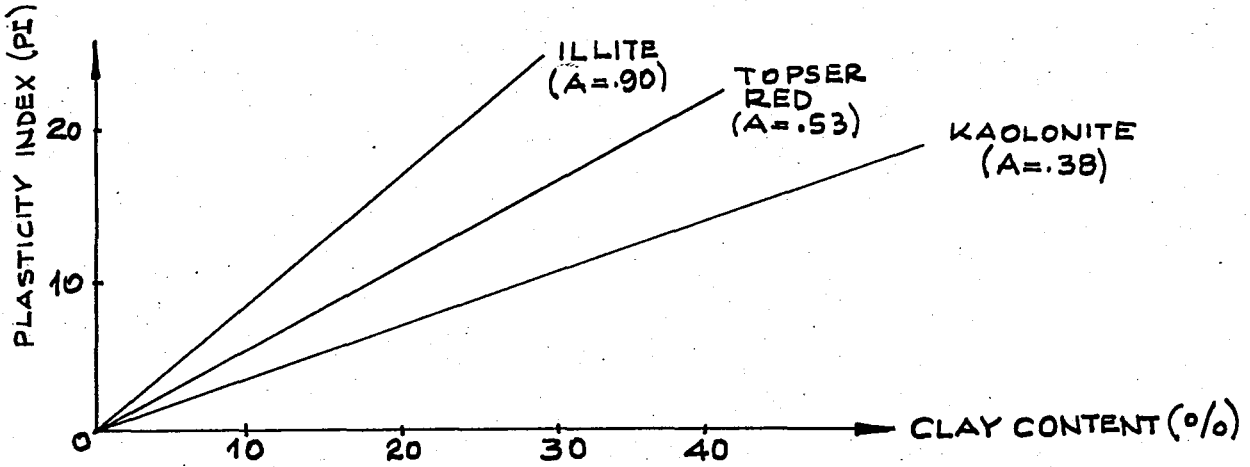
$$PL = 22.3 \%$$

$$PI = 15.8 \%$$

$$\text{Clay content} = 30 \%$$

$$\text{Therefore, Activity} = \frac{15.8}{30} = 0.53$$

Activity Diagram



The position of TOPSER-RED according to the activities of two main clay minerals illite and kaolonite is shown in the activity diagram above.¹⁵

2. Cement

(a) Properties of Cement Used. The cement used in this study was manufactured by the ASLAN Cement Factory. The properties of this cement are given below:

ASLAN ÇİMENTO

ASLAN VE ESKİŞEHİR MÜTTEHİT ÇİMENTO
VE SU KİREÇİ FABRİKALARI ANONİM ŞTİ.

Experiment No. : 15 197	Specific Gravity= 3.15
Date of Experiment : 6.4.1970	
Designation : NPÇ 350	

15. "Zemin Deneylerinde Gerekli Minimum Numune Sayısı," by Prof. Vahit Kumbasar and Doç. Dr. Ergün Toğrol, İTÜ, 1970.

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CHEMICAL AND PHYSICAL ANALYSIS OF CEMENT USED

Oxide Analysis

SiO_2 Free : 21.12 %
 SiO_2 Occupied: 0.36 %
 Al_2O_3 : 4.67 %
 Fe_2O_3 : 3.65 %
 CaO : 64.28 %
Free CaO : 0.10 %
 MgO : 1.24 %
 SO_3 : 2.89 %
 Na_2O, K_2O : ———
Ignition Loss : 0.96 %

Compounds (Calculated)

C_3S : 56.68 %
 C_2S : 17.88 %
 C_3A : 6.21 %
 C_4AF : 11.09 %

Fineness

Per cent passing sieve $A^\#$: 91.4 %
 $\#$ (10.000 holes in 1 cm^2)

Specific surface (Blaine): 2936 cm^2/gr

Setting time initial : 140 minutes
final : 270 minutes

Tensile Strength (kg/cm^2)			Compressive Strength (kg/cm^2)		
<u>3 Days</u>	<u>7 Days</u>	<u>28 Days</u>	<u>3 Days</u>	<u>7 Days</u>	<u>28 Days</u>
23	29	34	301.0	283.2	503.0
22	28	33	291.4	368.6	484.0
23	27	31	296.2	373.4	484.0
22.5	26.5	33	286.6	373.4	503.0
Mean: 22.6	27.6	33.5	Mean: 293.8	374.6	493.5

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B. APPARATUS

1. Vapour-Temperature Controlled Relative Humidity Chamber

This was used for curing the specimens at constant temperature for a given relative humidity.

It consists of stainless steel base section of such dimensions as to contain all necessary controls, motor and blower, water reservoir, cooling coils and heating elements. Top surface of this base section receives an inverted, cylindrical pyrex jar of standard size. The inverted jar forms the work chamber and the unit is sealed by rubber gaskets fitted to two inch high stainless band.

As shown in Figure 11, full visibility is assumed.

The blower intake opening is centrally positioned on top of the stainless steel base and concentric with the inner edges of the inverted pyrex jar. Air flow pattern is such that it withdraws air into center intake opening, passes over the humidifying and temperature controlling devices, and discharges this air upward along the inner sides of the jar. Then air is forced over the cooling coils. This cools the air to a proper dew point. This temperature depends upon the conditions being controlled and the corresponding wet bulb control setting. At the same time, air passes over an open water supply and approaches a saturated condition at the cooler temperature. The air is then passed over the dry bulb heater, where it is heated to the desired temperature depending upon the setting of the independent dry bulb control.

Since heated air can hold more water vapour than cool air, expressing the water vapour content of air in terms of humidity is because of this phenomenon.

Therefore, for any given dry bulb temperature, every specific temperature setting of chilled air will result in a specific corresponding relative humidity change within the chamber.

A given condition is easily obtained by first consulting a standard psychrometric chart to convert the desired temperature-humidity condition into wet bulb and dry bulb temperatures. Then these dry and wet bulb temperatures are set to correspond.

Moist Cabinet: It is a suitably covered container. It is capable of maintaining a temperature of $(21 \pm 2)^{\circ}\text{C}$, and a relative humidity of 95 per cent for storage of compacted soil-cement samples both for uncompressive testing and wetting-drying and freezing-thawing tests.

Freezing Cabinet: It was capable of maintaining a temperature of -25°C for the purpose of freezing the soil-cement samples for the freezing-thawing tests, (Fig. 10).

Water Bath: It was a suitable tank for submerging the compacted specimens in water at the room temperature.

2. Compaction, Weighing, Curing and Extruding Apparatus

Compaction Machine: Compaction machine was an automatic device adjustable to any number of blows. It had a metal rammer having a diameter of 5.08 cm (2 inches), circular arrangement face and a weight of 2490

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grams (5 pounds). This rammer was equipped with a suitable arrangement to control the height of drop to a free fall of 30.5 cm (12 inches) above the elevation of soil-cement, (Fig. 3).

Molds: Cylindrical metal molds each having a capacity of 945 cubic centimeters with an internal diameter of 11.63cm (4.584 inches). The mold was provided with a detachable collar approximately 6.35cm ($2\frac{1}{2}$ inches) in height (Fig. 4).

Mixer: This had a planetary mixing action so that the stainless steel beater reached every part of the batch, rotating on its axis opposite to the direction in which it moved around the bowl. This gave a very thorough blending and mixing of all the ingredients and ended in a consistent result in the finished mix. It was used throughout the testing period to mix soil-cement mixtures (Fig. 2).

Balances: One of the balances had a capacity of 15 kilograms, sensitive to 0.1 grams. The other balance was of 1000 grams capacity and was sensitive to 0.01 grams (Fig. 1, 8).

Drying Ovens: One of them was capable of maintaining a temperature of $(110 \pm 5)^{\circ}\text{C}$ for drying moisture samples. The other was a thermostatically controlled oven capable of maintaining a temperature between $(71 \pm 3)^{\circ}\text{C}$ and $(110 \pm 5)^{\circ}\text{C}$, for drying compacted soil-cement specimens, (Fig. 9).

Wire-Scratch Brush: This was made of No. 26 gauge, flat ($2\text{ inches} \times \frac{1}{16}\text{ inches}$) wire bristles, and was used for brushing the specimens (Fig. 9).

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Sample Extruder: A hydraulic jack for the purpose of extruding compacted specimens from the mold and from the thin walled tube, (Fig. 6).

Sample Extruding Tubes: These were metal tubes having an inside diameter of 3.81 cm and a height of 12 cm, used for extruding and keeping compacted specimens for unconfined compressive strength testing (Fig. 4) .

Unconfined Apparatus, Hand Operated: This had a load capacity of 1000 pounds and a sensitivity of $\frac{1}{10}$ pounds. Readings on the dial were converted to the load applied to the specimen by using a calibration curve. The loads were applied to the specimen through a gearing arrangement located in the totally enclosed metal base. The rate of strain was regulated during the test by turning the hand crank at the desired rate (Fig. 8).

The other gadgets were straightedges, No.4 Sieve, mixing tools, measuring devices, knives, graduates, moisture cans, and so on.

III. METHOD AND PROCEDURE

A. Method

The compaction of soil-cement mixtures, the wetting-drying tests, and freezing-thawing tests were performed according to the ASTM designations, D558, D559, and D560 respectively.¹⁶ The unconfined compressive strength tests and the tests for consistency indices of the soil and the soil-cement were conducted by usual test methods.

For the wetting-drying and freezing-thawing tests standard size specimens, 4 inches in diameter and 4.6 inches in height were molded at cement contents of 6, 9, 12 and 15 per cent on dry weight basis and moist-cured for 7 days before the freeze-thaw and wet-dry tests.

The freeze-thaw and wet-dry tests were conducted on specimens prepared as explained above to determine length (volume) changes, moisture changes and soil-cement losses. Standard brushing procedures¹⁷ were used to determine losses. Periodical weight and length measurements were taken during the tests, to determine the deterioration of soil-cement samples in either of the tests.

Compressive strength was determined after certain periods of moist curing on the specimens obtained from the compacted soil-cement mixtures. In all the cases, the specimens were soaked for one hour

16, 17. American Society for Testing Materials, Designation D558 "Standard Method of Test For Moisture-Density Relations of Soil-Cement Mixtures."
ASTM, Designation D559, "Standard Method of Wetting-and-Drying Test of Compacted Soil-Cement Mixtures."
ASTM, Designation D560, "Standard Method of Freezing-and-Thawing Test of Compacted Soil-Cement Mixtures."

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fore being tested. A flow diagram for the testing procedure is given the following page.

A total amount of 298 samples were tested for compaction, wetting-drying, freezing-thawing and unconfined compressive strength in addition to those used to determine the consistency indices of soil-cement mixtures. The number of samples tested for different purposes are given in the following table.

Name of the Test	Number of Samples Tested
The Compaction Test to determine the optimum water content and maximum dry density of soil.	36
Unconfined compressive strength test of soil molded at optimum water content, below optimum above optimum and under different compaction energies.	30
The compaction tests for soil-cement to determine optimum water content and maximum dry density of each soil-cement mixture.	24
Wetting-drying tests	24
Freezing-thawing tests	16
Unconfined compressive strength tests to determine: a) Effect of curing time (age) b) Effect of temperature c) Effect of density d) Effect of water content	72 40 32 24
Tests for consistency indices	LL, PL for each soil-cement

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1. FLOW DIAGRAM OF TESTING PROCEDURE

Preparation of Soil

Determination of optimum moisture content, maximum dry density and unconfined compressive strength of the soil

Determination of consistency limits, optimum water content, max. dry density of soil-cement mixtures containing 6, 9, 12 and 15 percent cement

Molding of soil-cement mixtures at optimum water content

UNCONFINED COMPRESSION TEST for

- a) Age effect
- ** b) Temperature effect
- c) effect of density
- * d) effect of water content
- e) effect of cement content

Curing in moist room for specific periods

1 hour submerging in water before testing

Unconfined compression test

Computation of unconfined compressive strength

WET-DRY TEST

7-day curing in moist room

5-hour submerging in potable water

42-hour oven drying at 71°C

12-cycles of wet-dry test

Drying of specimens to constant weight at 110°C

Computation of percentage weight losses and length (volume) changes

FREEZE-THAW TEST

7-day curing in moist room

Freezing for 24 hour $T < -24^{\circ}$

Thawing for 24-hour

12-cycles of freeze-thaw test

- * - Samples also were tested above and below optimum water content
- ** - Specimens were cured in a special * vapor-temp relative humidity chamber

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B. Procedure 19

Determination of Moisture-Density Relations of Soil-Cement Mixtures

The sample was first dried by air until it was friable under trowel. Then the sample was broken down until it passed a No.4 (76mm) sieve. Then the natural moisture content of air-dried soil was determined and recorded.

After this, a representative sample weighing approximately 10 kilograms was selected of the soil prepared above. The required amount of cement (first six per cent, on dry soil weight basis) was added to the soil. Then the cement and soil were thoroughly mixed in a mixer (Fig.2) to a uniform colour. Sufficient water was added to open the mixture to approximately three per cent points below the estimated optimum moisture content and the soil was mixed thoroughly.

Then a specimen was prepared by compacting the ready soil-cement mixture in the mold, in three equal layers. Each layer was compacted by 25 blows from the rammer dropping free from a height of 30 centimeters above the elevation of soil-cement.

After compaction, the compacted mixture was trimmed even with the top of the mold, weighed and the unit wet weight of soil-cement was determined. Following this, the material was removed from the mold and a representative sample was taken for the moisture content determination.

The remainder of the material was removed from the mold, thoroughly broken down until it could pass a No.4 sieve and a sufficient

According to ASTM D558, D559, D560.

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amount of water was added to increase the moisture content of the soil-cement mixture by three per centage points. Then the soil was mixed and the procedure given above was repeated for each increment of water added. This series of determinations were repeated until there was either a decrease or no change in the wet unit weight of compacted soil-cement mixture.

The above operations were repeated for cement contents of six, nine, 12 and 15 per cents. After dry unit weights and corresponding moisture contents for the particular soil were determined, proctor curves were drawn and optimum water contents and maximum dry densities were determined for each soil-cement mixture.

These determinations of optimum moisture contents and maximum dry densities for each soil-cement mixture were performed twice and the average values were taken to draw the proctor curves.

2. Preparation of Specimens for Freezing-Thawing and Wetting-Drying Tests

After the optimum moisture content was determined for each soil-cement mixture, about 9 kilograms of soil were prepared for the freezing-thawing and wetting-drying tests, (Fig. 1).

A required amount of cement was added to soil, they were mixed thoroughly to a uniform colour and sufficient water was added to raise the soil-cement mixture to optimum moisture content at the time of compaction and mixed for five minutes. Two specimens were formed in

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two different proctor molds after mixing. Each specimen was compacted in three equal layers in the compaction machine. Top of the first and second layers were scarified before compacting the succeeding layers. Meanwhile, representative samples were taken for water content determinations. The compacted specimens were removed from the mold, and weighed. One of the specimens was identified as No.1 to obtain data on moisture and volume changes during the test. The second specimen was identified as No.2 specimen to obtain data on soil-cement losses during the test.

Then the height and diameter of No.1 specimen were measured and both of the specimens were placed in moist cabinet for a curing period of seven days. During this interval, they were protected from free water. The above operations were repeated for specimens containing six, nine, 12 and 15 per cents of cement on dry soil weight basis, both for the wetting-drying and freezing-thawing tests.

a) Wetting-Drying Tests. At the end of storage in the moist room for seven days, the specimens were submerged in water at room temperature (21.5°C) for a period of five hours and then they were removed, (Fig. 9). The No.1 specimen was weighed and measured. The No.2 specimen was weighed and then by holding a standard brush parallel to the longitudinal axis of the sample, 20 strokes were applied to the full height covering all areas, and four strokes were applied to each end of the sample. Then the No.2 specimen was weighed to find the soil-cement

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ss on drying. Thus, one cycle of wetting and drying (48 hours) was completed. Again the specimens were submerged in water and the procedure was repeated for 12 cycles.

After 12 cycles of the test, the specimens were dried to constant weight at 110°C and weighed to determine to oven-dry weights.

Upon completion of 12 cycles, the soil-cement losses and volume and moisture changes were calculated for No.2 and No.1 specimens respectively.

) Freezing-Thawing Tests. At the end of the storage in the moist room, water saturated pads about 0.5 centimeters in thickness were placed between the specimens. Then the assembly was placed in a freezing cabinet having a constant temperature of -25°C for 24 hours and removed. The No.1 specimen was then weighed and measured.

The whole assembly was taken to a humidity cabinet having a relative humidity of 95 per cent and temperature of 21.5°C , and removed after 23 hours. Meanwhile, free portable water was made available the absorbent pads under the specimen to permit the specimens to absorb water by capillary action during the thawing period. Upon removal of the samples from the humidity cabinet, the No.1 specimen was weighed and measured, the No.2 specimen was weighed and brushed and then weighed again as in the wetting and drying test.

The procedures given above constituted one cycle of the freezing-thawing test. Again the specimens were placed in the freezing

cabinet (Fig.10) and the procedure was continued for 12 cycles. The weight determinations of No.2 specimen as described above were made before and after brushing at the end of each cycle.

3. Unconfined Compression Tests

These tests were conducted to determine the effects of:

- (a) age;
- (b) temperature;
- (c) density;
- (d) water content.²⁰

The soil-cement specimens were compacted at optimum water content as in the freezing-thawing and wetting-drying tests. Following compaction, the extension collar was removed, compacted mixture was carefully trimmed even with the top of the mold by means of a knife and a straightedge.

Then a specially made thin walled small tube having a constant inside diameter of 3.81 centimeters and a length of 12 centimeters was forced into the mold by the use of the hydraulic press (Figs. 4, 5,6). Then the whole assembly was taken out of the mold. Another wooden sample extruder having a diameter of 3.78 centimeters was used to extrude the sample from the tube by using the hydraulic press again. Then the top and bottom of the sample were trimmed and it was weighed and measured. The samples were kept in the moist humidity cabinet at 21.0°C (Fig.7), for specific periods and tested for the

²⁰. Samples were compacted at above and below optimum water content, as well as at the optimum level.

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unconfined compressive strength to determine the age effect.

The samples used to determine the effect of temperature were cured before testing, in a special "vapour-temperature humidity chamber" having a relative humidity of 95 per cent.

The samples prepared to find the effect of density were given 15, 20, 25, 30, 35 blows from the rammer to obtain different densities at optimum water content.

The soil-cement samples, to find the effect of water content, were molded 3-4 per centage points above and below optimum water content and also at optimum water content.

All the samples for compressive strength testing were submerged in water for one hour, prior to testing.

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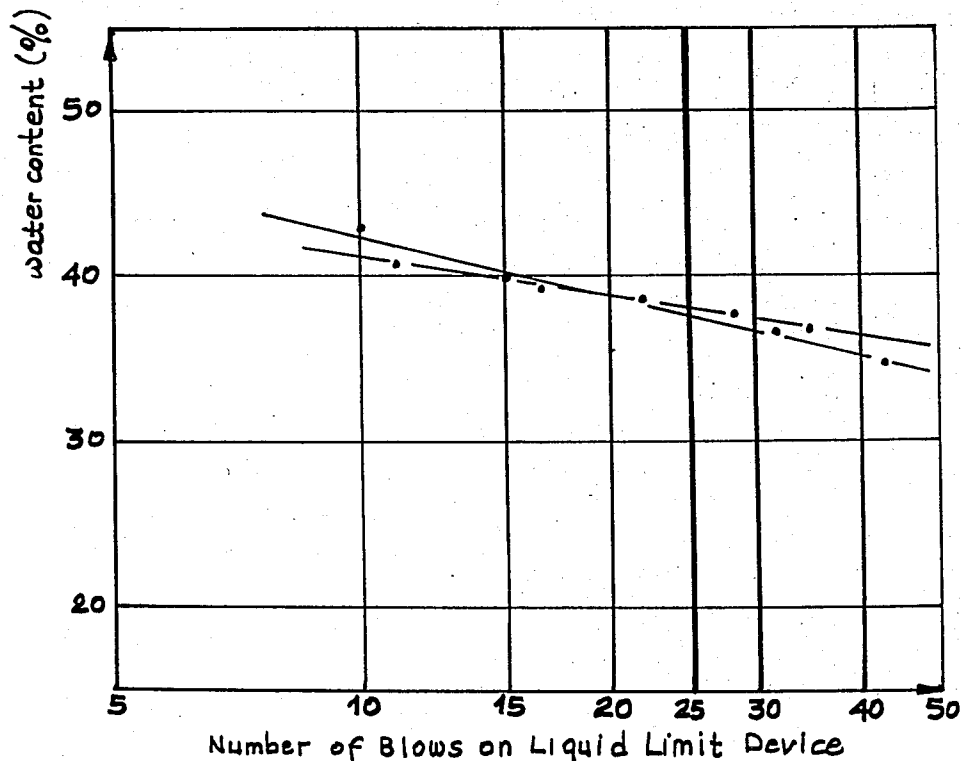
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4. Effects of Cement Content On Consistency Indices of Soil

Cement Content	TEST 1							TEST 2						
		LL					PL	LL					PL	RESULTS
0%	N [±]	11	18	22	28	35	—	10	15	22	32	43	—	LL = 38.0
	W% [±]	40.8	39.3	38.6	37.7	36.8	22.7	42.7	39.9	38.5	36.7	34.7	22.9	PL = 22.8
6%	N	10	15	20	27	44	—	11	15	25	36	44	—	LL = 42.1
	W%	50.0	46.0	44.1	42.3	37.6	26.2	48.0	45.9	42.2	39.6	38.3	26.2	PL = 26.2
9%	N	9	13	23	34	35	—	8	16	34	45	—	—	LL = 41.8
	W%	48.0	45.9	42.3	39.8	33.0	27.5	49.9	44.9	39.7	43.1	—	27.1	PL = 27.3
12%	N	8	13	20	32	47	—	9	15	27	40	—	—	LL = 41.0
	W%	47.5	45.1	42.2	40.0	36.7	26.8	48.9	44.7	40.1	36.8	—	27.1	PL = 27.0
15%	N	11	21	33	39	48	—	7	12	21	25	43	—	LL = 40.5
	W%	44.6	41.0	35.0	39.3	38.0	26.8	43.5	42.4	41.1	40.5	39.5	26.8	PL = 26.8

N = Number of blows
W% = per cent water content



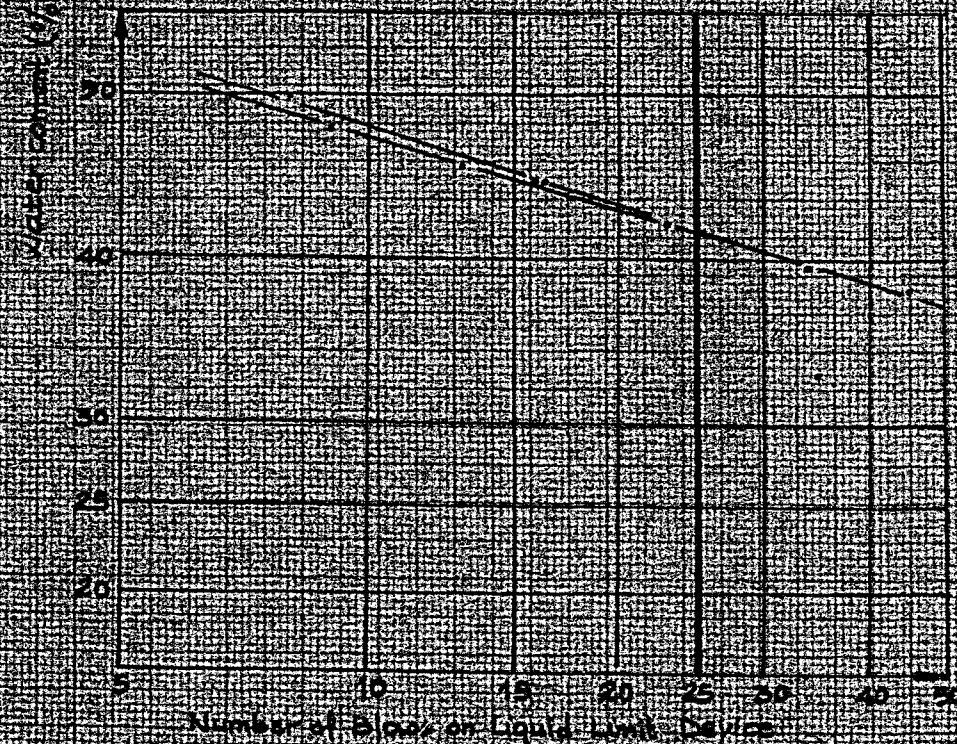
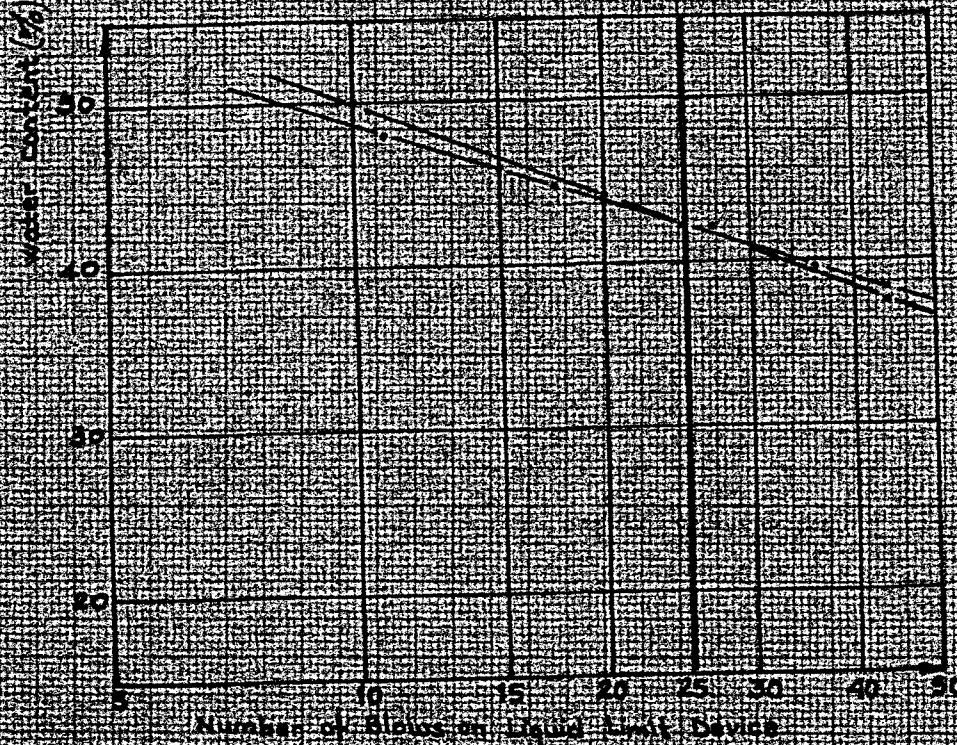
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CONSISTENCY INDICES FOR SOIL-CEMENT MIXTURES

FLOW CURVES

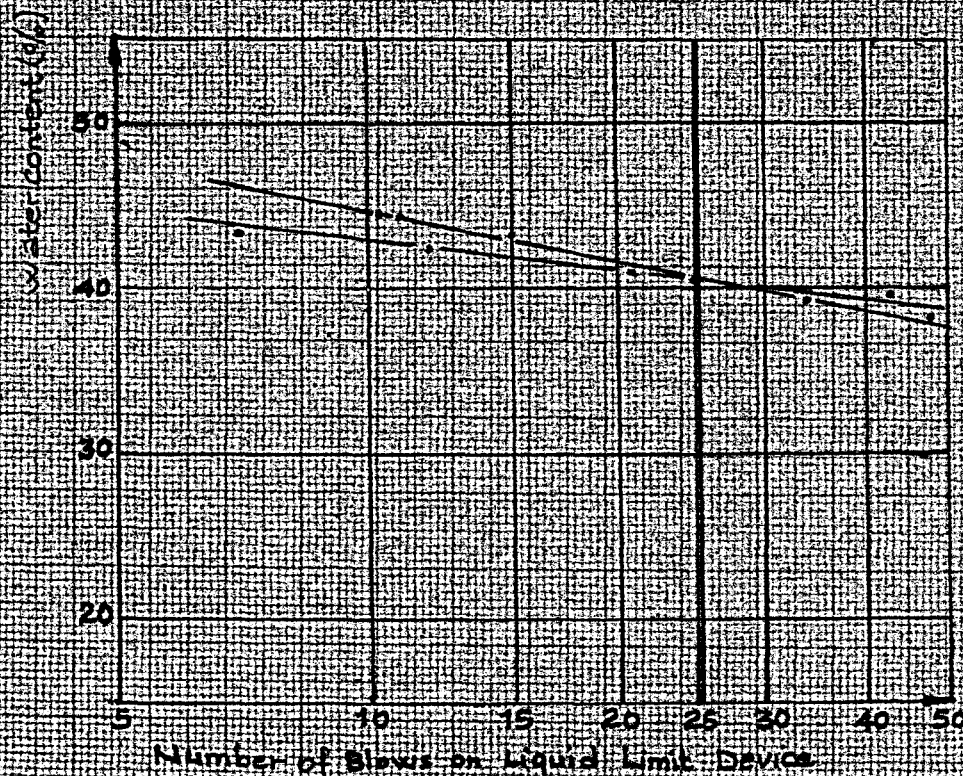
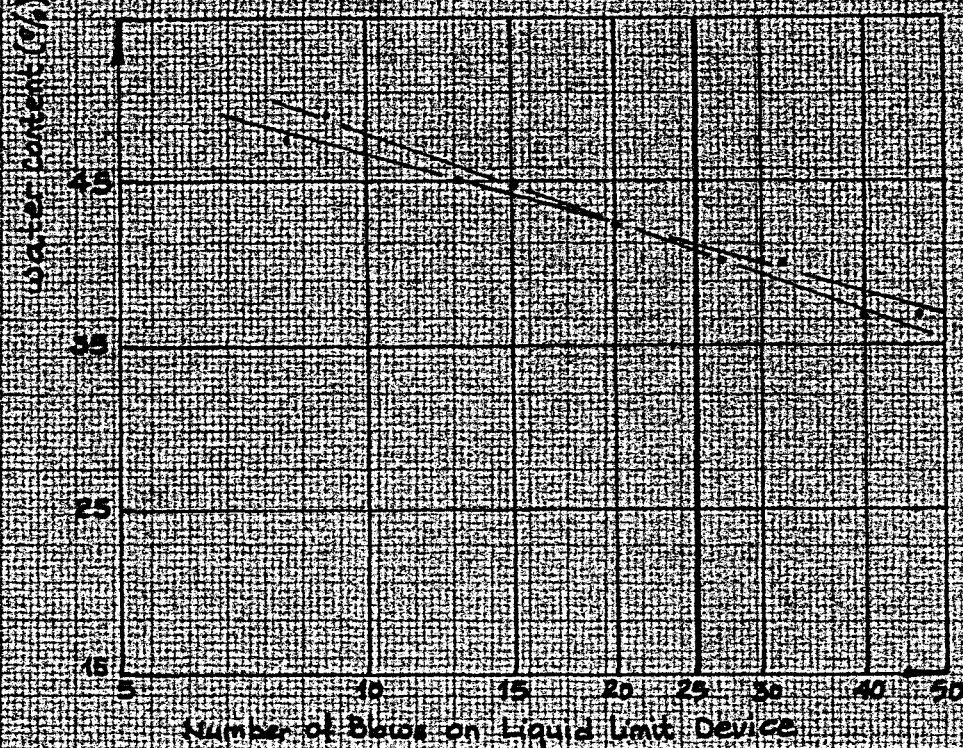


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Flow Curves (continued)



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IV. DATA, RESULTS, DISCUSSION and CONCLUSION

A. Data

Wet-Dry Tests 9 %
Soil-Cement Loss Data

	Sample A		Sample B	
	Compacted Sample	After 7-day Curing Period	Compacted Sample	After 7-day Curing Period
r)	2,039	2,045	2,024	2,025
m)	11.76	11.77	11.77	11.77
m)	10.18	10.20	10.18	10.18
)	13.88	—	13.57	13.57

$$\gamma_n = 2.13 \text{ gr/cm}^3$$

$$\gamma_d = 1.87 \text{ gr/cm}^3$$

$$\gamma_n = 2.12 \text{ gr/cm}^3$$

$$\gamma_d = 1.86 \text{ gr/cm}^3$$

Weight of Sample When Dried at 71°C (gr)					
Sample No.	Curing Time	Before Brushing	After Brushing	Before Brushing	After Brushing
1	48 hr.	1,720	1,690	1,798	1,771
2		1,659	1,623	1,718	1,683
3		1,586	1,557	1,672	1,643
4		1,547	1,513	1,626	1,600
5		1,507	1,486	1,576	1,551
6		1,486	1,471	1,543	1,528
7		1,469	1,457	1,512	1,469
8		1,457	1,445	1,438	1,421
9		1,444	1,430	1,417	1,400
10		1,435	1,421	1,396	1,386
11		1,423	1,403	1,382	1,371
12		1,409	1,398	1,370	1,362
Weight at 110°C		1,390		1,349	

REMARKS: 6 % soil-cement samples disintegrated in water when submerged for a 5-hour period in the curing tank.

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Wet-Dry Tests Soil-Cement Loss Data 12 %

	Sample A		Sample B	
	Compacted Sample	After 7-day Curing Period	Compacted Sample	After 7-day Curing Period
gr)	2,041	2,030	2,038	2,036
cm)	11.77	11.78	11.75	11.75
cm)	10.18	10.19	10.18	10.18
%)	14.40	—	14.10	—

$$\gamma_n = 2.14 \text{ gr/cm}^3$$

$$\gamma_d = 1.87 \text{ gr/cm}^3$$

$$\gamma_n = 2.14 \text{ gr/cm}^3$$

$$\gamma_d = 1.87 \text{ gr/cm}^3$$

Weight of Sample When Dried at 71°C (gr)

Sample No.	Curing Time	Before Brushing	After Brushing	Before Brushing	After Brushing
1	48 hr	1,800	1,670	1,863	1,810
2		1,658	1,640	1,800	1,762
3		1,644	1,620	1,751	1,727
4		1,627	1,614	1,716	1,701
5		1,613	1,600	1,689	1,649
6		1,600	1,586	1,643	1,631
7		1,588	1,572	1,626	1,598
8		1,576	1,560	1,591	1,587
9		1,559	1,551	1,588	1,577
10		1,554	1,548	1,570	1,563
11		1,546	1,533	1,558	1,550
12		1,531	1,526	1,554	1,543
Weight at 110°C		1,516		1,527	

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Wet-Dry Tests Soil-Cement Loss Data 15 %

	SAMPLE A		SAMPLE B	
	Compacted Sample	After 7-day Curing Period	Compacted Sample	After 7-day Curing Period
gr)	2,017	2,013	2,038	2,035
cm)	11.76	11.75	11.74	11.74
cm)	10.18	10.18	10.18	10.18
%)	14.40		14.86	

$$\gamma_n = 2.11 \text{ gr/cm}^3$$

$$\gamma_d = 1.85 \text{ gr/cm}^3$$

$$\gamma_n = 2.14 \text{ gr/cm}^3$$

$$\gamma_d = 1.86 \text{ gr/cm}^3$$

Weight of Sample When Dried at 71°C (gr)					
Sample No	Curing Time	Before Brushing	After Brushing	Before Brushing	After Brushing
1	48 hr.	2,019	1,936	2,011	1,971
2		1,900	1,887	1,943	1,938
3		1,802	1,780	1,930	1,913
4		1,783	1,773	1,891	1,883
5		1,775	1,766	1,885	1,870
6		1,768	1,757	1,841	1,829
7		1,759	1,751	1,817	1,800
8		1,750	1,740	1,796	1,786
9		1,741	1,734	1,787	1,768
10		1,734	1,726	1,763	1,742
11		1,730	1,721	1,728	1,709
12		1,723	1,717	1,711	1,699

Weight at 110°C 1,698 1,689

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Wet -Dry Tests

Soil-Cement Loss Data, Above and below
maximum dry density

Wet weight of Sample (W_n - gr)	Dry density (gr/cm^3)	Water Content(%)	Weight of Sample at $110^\circ C$ (gr)
1,962	1.81	13.69	1,153
1,981	1.83	13.80	1,228
2,076	1.90	13.96	1,548
2,080	1.92	13.68	1,478
1,979	1.81	14.25	1,292
2,015	1.84	14.36	1,400
2,069	1.89	14.80	1,637
2,091	1.91	14.31	1,621
1,978	1.80	14.96	1,491
2,008	1.82	15.30	1,681
2,058	1.88	14.50	1,752
2,074	1.89	14.73	1,791

MARKS: 6 % soil-cement samples deteriorated in water.

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Freeze-Thaw Tests

Volume and Moisture Change Data

6 % (a)

Volume and Moisture Change specimen A

	Compacted Specimen	Specimen after 7-day curing
W(gr)	2,038	2,036
h(cm)	11.77	11.77
d(cm)	10.18	10.18
w(%)	13.36	

$$\gamma_n = 2.13 \text{ gr/cm}^3$$

$$\gamma_d = 1.88 \text{ gr/cm}^3$$

Cycle No.	Curing Time	Freezing Length (cm)	Thawing Length (cm)	Freezing Weight (gr)	Thawing Weight (gr)
1	48 hr.	11.79	11.83	2,039	2,093
2		11.82	11.89	2,084	2,098
3		11.87	12.03	2,067	2,090
4		11.94	12.11	2,081	2,110
5		12.08	12.17	2,189	2,098
6		FE			
7					
8					
9					
10					
11					
12					

REMARKS: * Sample was disintegrated after 5 cycles of the freeze-thaw test.

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Freeze-Thaw Tests

Volume and Moisture Change Data

6 % (b)

Volume and Moisture Change Specimen B

	Compacted Specimen	Specimen after 7-day curing
W(gr)	2.038	2.028
h(cm)	11.76	11.74
d(cm)	10.18	10.17
w(%)	12.90	

$$\gamma_n = 2.13 \text{ gr/cm}^3$$

$$\gamma_d = 1.89 \text{ gr/cm}^3$$

Cycle No.	Curing Time	Freezing Length (cm)	Thawing Length (cm)	Freezing Weight (gr)	Thawing Weight (gr)
1	48 hr.	11.84	11.92	2.031	2.083
2		11.89	12.02	2.071	2.096
3		11.93	12.11	2.087	2.111
4		12.00	12.17	2.098	2.099
5		#			
6					
7					
8					
9					
10					
11					
12					

REMARKS: Sample disintegrated after 4 cycles of the freeze-thaw test.

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Freeze-Thaw Tests

Volume and Moisture Change Data

9 % (a)

Volume and Moisture Change Specimen A

	Compacted Specimen	Specimen after 7-day curing
W(gr)	2,038	2,043
h(cm)	11.77	11.78
d(cm)	10.18	10.19
w(%)	14.00	

$$\gamma_n = 2.13 \text{ gr/cm}^3$$

$$\gamma_d = 1.87 \text{ gr/cm}^3$$

Cycle No.	Curing Time	Freezing Length (cm)	Thawing Length (cm)	Freezing Weight (gr)	Thawing Weight (gr)
1	48 hr.	11.79	11.83	2,045	2,112
2		11.82	11.85	2,096	2,144
3		11.87	11.94	2,126	2,136
4		11.86	11.91	2,133	2,138
5		11.93	11.97	2,129	2,132
6		11.95	12.03	2,130	2,139
7		11.94	12.01	2,124	2,135
8		11.94	12.04	2,133	2,145
9		11.97	12.03	2,136	2,140
10		12.03	12.05	2,136	2,143
11		12.04	12.09	2,139	2,142
12		12.06	12.15	2,138	2,142

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The Freeze-Thaw Tests Volume and Moisture Change Data 9 % (b)

	Volume and Moisture Change Specimen B	
	Compacted Specimen	Specimen after 7-day curing
W(gr)	2,059	2,060
h(cm)	11.76	11.77
d(cm)	10.18	10.18
w(%)	14.43	

$$\gamma_n = 2.15 \text{ gr/cm}^3$$

$$\gamma_d = 1.88 \text{ gr/cm}^3$$

Cycle No.	Curing Time	Freezing Length (cm)	Thawing Length (cm)	Freezing Weight (gr)	Thawing Weight (gr)
1	48 hr.	11.80	11.84	2,061	2,089
2		11.83	11.85	2,079	2,112
3		11.85	11.89	2,094	2,123
4		11.86	11.87	2,111	2,120
5		11.91	11.94	2,113	2,130
6		11.89	11.95	2,122	2,138
7		11.93	11.97	2,119	2,132
8		11.97	12.00	2,121	2,129
9		11.96	12.02	2,124	2,127
10		11.98	12.05	2,126	2,134
11		12.04	12.03	2,180	2,233
12		12.05	12.07	2,182	2,233

THESIS

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Freeze Thaw Tests

Volume and Moisture Change Data

12 % (a)

Volume and Moisture Change Specimen A

	Compacted Specimen	Specimen after 7-day curing
W (gr)	2,036	2,036
L (cm)	11.77	11.77
A (cm)	10.18	10.18
W (%)	14.30	14.30

$$\gamma_n = 2.13 \text{ gr/cm}^3$$

$$\gamma_d = 1.86 \text{ gr/cm}^3$$

Cycle No.	Curing Time	Freezing Length (cm)	Thawing Length (cm)	Freezing Weight (gr)	Thawing Weight (gr)
1	48 hr.	11.81	11.84	2,037	2,096
2		11.84	11.88	2,083	2,113
3		11.86	11.93	2,099	2,131
4		11.90	11.89	2,127	2,143
5		11.91	11.97	2,141	2,156
6		11.90	11.94	2,144	2,149
7		11.94	11.99	2,145	2,161
8		11.96	11.98	2,158	2,172
9		11.99	12.05	2,158	2,168
10		12.02	12.07	2,156	2,181
11		12.05	12.10	2,166	2,189
12		12.06	12.09	2,180	2,178

THESIS

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Freeze-Thaw Tests

Volume and Moisture Change Data

12 % (b)

Volume and Moisture Change Specimen B

	Compacted Specimen	Specimen after 7-day curing
gr)	2,041	2,043
cm)	11.75	11.76
cm)	10.18	10.18
%)	14.51	

$$\gamma_n = 2.14 \text{ gr/cm}^3$$

$$\gamma_d = 1.87 \text{ gr/cm}^3$$

Specimen No.	Curing Time	Freezing Length (cm)	Thawing Length (cm)	Freezing Weight (gr)	Thawing Weight (gr)
1	48 hr.	11.77	11.81	2,046	2,089
2		11.79	11.82	2,073	2,098
3		11.82	11.85	2,095	2,106
4		11.86	11.89	2,089	2,108
5		11.85	11.89	2,100	2,117
6		11.88	11.96	2,114	2,136
7		11.93	11.99	2,129	2,149
8		11.95	12.02	2,143	2,166
9		11.99	12.08	2,152	2,168
10		12.00	12.07	2,159	2,179
11		12.02	12.06	2,167	2,186
12		12.01	12.08	2,174	2,183

THESIS

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Freeze-Thaw Tests

Volume and Moisture Change Data

15 % (a)

Volume and Moisture Change Specimen A

	Compacted Specimen	Specimen after 7-day curing
W (gr)	2,042	2,040
L (cm)	11.76	11.78
d (cm)	10.18	10.18
v (%)	14.92	

$$\gamma_n = 2.14 \text{ gr/cm}^3$$

$$\gamma_d = 1.86 \text{ gr/cm}^3$$

Cycle No.	Curing Time	Freezing Length (cm)	Thawing Length (cm)	Freezing Weight (gr)	Thawing Weight (gr)
1	48 hr.	11.78	11.81	2,056	2,096
2		11.81	11.85	2,083	2,126
3		11.80	11.87	2,120	2,127
4		11.84	11.86	2,123	2,139
5		11.85	11.89	2,136	2,139
6		11.86	11.88	2,140	2,148
7		11.85	11.90	2,145	2,157
8		11.87	11.93	2,150	2,163
9		11.90	11.96	2,148	2,160
10		11.92	11.97	2,156	2,166
11		11.91	11.96	2,161	2,171
12		11.94	11.98	2,162	2,170

THESIS

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Freeze-Thaw Tests

Volume and Moisture Change Data

15 % (b)

Volume and Moisture Change Specimen B

	Compacted Specimen	Specimen after 7-day curing
W(gr)	2,062	2,056
h(cm)	11.78	11.77
d(cm)	10.18	10.18
w(%)	15.10	

$$\gamma_n = 2.15 \text{ gr/cm}^3$$

$$\gamma_d = 1.87 \text{ gr/cm}^3$$

Cycle No.	Curing Time	Freezing Length (cm)	Thawing Length (cm)	Freezing Weight (gr)	Thawing Weight (gr)
1	48 hr.	11.79	11.82	2,063	2,128
2		11.81	11.83	2,098	2,136
3		11.82	11.85	2,099	2,143
4		11.82	11.87	2,127	2,146
5		11.83	11.86	2,133	2,145
6		11.83	11.87	2,139	2,157
7		11.86	11.89	2,141	2,161
8		11.85	11.91	2,146	2,188
9		11.89	11.93	2,160	2,186
10		11.90	11.92	2,158	2,189
11		11.93	11.95	2,179	2,185
12		11.95	11.98	2,181	2,186

THESIS

ROBERT COLLEGE GRADUATE SCHOOL
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Freeze-Thaw Tests Soil-Cement Loss Data 6 %

Sample A			Sample B	
	Compacted Sample	After 7-day Curing Period	Compacted Sample	After 7-day Curing Period
W (gr)	2,034	2,017	2,028	2,026
h (cm)	11.78		11.76	
d (cm)	10.18		10.18	
w (%)	13.50		12.98	
$\gamma_n = 2.12 \text{ gr/cm}^3$ $\gamma_d = 1.87 \text{ gr/cm}^3$			$\gamma_n = 2.12 \text{ gr/cm}^3$ $\gamma_d = 1.88 \text{ gr/cm}^3$	

Weight of Sample When Dried at 71°C (gr)					
Cycle No.	Curing Time	Before Brushing	After Brushing	Before Brushing	After Brushing
1	48 hr.	2,009	1,987	2,003	1,981
2		2,028	1,940	1,979	1,947
3		1,941	1,900	1,955	1,918
4		1,882	1,768	1,911	1,891
5		✖		1,879	1,817
6				1,802	1,779
7				✖✖	
8					
9					
10					
11					
12					
Weight at 110°C			1,698	1,718	

REMARKS:

- ✖ Sample deteriorated after 4 cycles of the freeze-thaw test.
- ✖✖ Sample deteriorated after 6 cycles of the freeze-thaw test.

THESIS

ROBERT COLLEGE GRADUATE SCHOOL
BEBEK, ISTANBUL

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Freeze-Thaw Tests Soil-Cement Loss Data 9 %

Sample A			Sample B	
	Compacted Soil	After 7-day Curing Period,	Compacted Sample	After 7-day Curing Period
W(gr)	2,048	2,051	2,017	2,015
h(cm)	11.78	11.78	11.75	
d(cm)	10.18	10.19	10.18	
w(%)	13.90	—	13.67	

$$\gamma_n = 2.14 \text{ gr/cm}^3$$

$$\gamma_d = 1.88 \text{ gr/cm}^3$$

$$\gamma_n = 2.11 \text{ gr/cm}^3$$

$$\gamma_d = 1.86 \text{ gr/cm}^3$$

Weight of Sample When Dried at 71°C (gr)					
Cycle No.	Curing Time	Before Brushing	After Brushing	Before Brushing	After Brushing
1	48 hr.	2,027	1,966	2,000	1,976
2		1,993	1,952	1,963	1,918
3		1,958	1,953	1,921	1,897
4		1,931	1,900	1,893	1,861
5		1,891	1,867	1,847	1,805
6		1,872	1,825	1,800	1,754
7		1,831	1,803	~~1,761~~	
8		1,796	1,746		
9		~~1,754~~			
10					
11					
12					
Weight at 110°C			1,696	1,703	

REMARKS:

- * Sample disintegrated after 8 cycles of freeze-thaw test.
- ** Sample disintegrated after 6 cycles of freeze-thaw test.

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Freeze-Thaw Tests Soil-Cement Loss Data 12 %

	SAMPLE A		SAMPLE B	
	Compacted Sample	After 7- Day curing period	Compacted Sample	After 7- DAY curing period
W(gr)	2043	2051	2026	2029
h(cm)	11.78	11.78	11.74	11.75
d (cm)	10.18	10.19	10.18	10.18
w(%)	13.96	—	14.40	—

$$\gamma_n = 2.14 \text{ gr/cm}^3$$

$$\gamma_d = 1.87 \text{ gr/cm}^3$$

$$\gamma_n = 2.13 \text{ gr/cm}^3$$

$$\gamma_d = 1.86 \text{ gr/cm}^3$$

Weight of sample when dried at 71° C (gr)

Cycle No	Curing time	Before Brushing	After Brushing	Before Brushing	After Brushing
1	48	2036	1986	2000	1937
2		1991	1955	1968	1941
3		1951	1905	1937	1901
4		1902	1884	1905	1876
5		1862	1833	1853	1839
6		1826	1793	1837	1800
7		1796	1759	1796	1771
8		1755	1728	1775	1736
9		1719	1698	1726	1679
10		1675	1646	1673	1617
11		1651	1611	1621	1599
12		1603	1597	1590	1561

Weight at 110° C 1555

1505

REMARKS : Both samples had good appearance and completed the 12 cycles.

THESIS

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Freeze-Thaw Tests Soil-Cement Loss Data 15 %

Sample A			Sample B	
	Compacted Sample	After 7-day Curing Period	Compacted Sample	After 7-day Curing Period
W(gr)	2,040	2,037	2,024	2,024
h(cm)	11.78	11.73	11.73	11.73
d(cm)	10.18	10.18	10.18	10.18
w(%)	14.96	14.73	14.73	
$\gamma_n = 2.10 \text{ gr/cm}^3$ $\gamma_d = 1.85 \text{ gr/cm}^3$			$\gamma_n = 2.13 \text{ gr/cm}^3$ $\gamma_d = 1.86 \text{ gr/cm}^3$	

Weight of Sample When Dried at 71°C (gr)					
Cycle No.	Curing Time	Before Brushing	After Brushing	Before Brushing	After Brushing
1	48 hr.	2,026	1,986	2,002	1,979
2		1,993	1,974	1,968	1,945
3		1,962	1,945	1,947	1,931
4		1,943	1,931	1,922	1,910
5		1,933	1,924	1,903	1,889
6		1,918	1,903	1,881	1,863
7		1,897	1,876	1,860	1,843
8		1,869	1,844	1,846	1,827
9		1,847	1,829	1,819	1,803
10		1,830	1,812	1,800	1,791
11		1,801	1,792	1,793	1,786
12		1,789	1,776	1,781	1,767
Weight at 110°C			1,756	1,719	

REMARKS: Both samples had good appearance and were not deteriorated.

AGE EFFECT: UNCONFINED COMPRESSIVE STRENGTHS
OF SOIL - CEMENT MIXTURES COM-
PACTED AT OPTIMUM WATER CONTENT

CEMENT CONTENT : 6 %
CURING TEMPERATURE : 21.5 °C
RELATIVE HUMIDITY : 95 %

$W_{opt} = 13.3 \%$ $\gamma_{dry} = 1.89 \text{ g/cm}^3$	AGE OF CURING ————— DAYS											
	0		3		7		14		21		28	
	A	B	A	B	A	B	A	B	A	B	A	B
W_i (gr)	193.71	192.00	194.00	190.82	190.51	185.00	189.00	180.53	195.00	191.20	187.81	187.72
W_F (gr)	192.27	191.89	193.91	190.29	190.12	184.32	188.76	—	194.30	190.25	186.58	186.45
h_i (cm)	8.01	7.88	7.96	7.93	7.81	7.72	7.83	7.88	7.96	7.88	7.69	7.70
d (cm)	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81
A (cm ²)	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4
γ_n (gr/cm ³)	2.12	2.14	2.14	2.11	2.14	2.10	2.12	2.07	2.15	2.13	2.14	2.14
ω_i (%)	12.98	13.34	13.41	12.89	13.27	12.80	13.02	10.76	13.81	13.09	13.34	13.00
ω_F (%)	12.00	13.03	13.07	12.57	12.99	11.97	12.48	—	13.40	12.67	12.89	12.51
γ_d (gr/cm ³)	1.88	1.89	1.89	1.87	1.89	1.87	1.88	1.86	1.89	1.88	1.89	1.89
DIAL READING (in $\times 10^{-4}$)	120	121	130	132	136	133	169	112	232	226	361	361
P (lbs)	110	112	116	118	125	121	156	98	204	199	330	331
P (kg)	49.9	50.3	52.6	53.5	56.6	54.9	62.4	44.5	92.5	90.2	149.7	150.0
q_u (kg/cm ²)	4.37	4.41	4.61	4.70	4.96	4.81	4.59	3.90	8.11	7.91	13.1	13.2

AGE EFFECT : UNCONFINED COMPRESSIVE STRENGTHS
OF SOIL-CEMENT MIXTURES COM-
PACTED AT OPTIMUM WATER CONTENT

CEMENT CONTENT : 9 %
CURING TEMPERATURE: 21.5 °C
OPTIMUM HUMIDITY : 95 %

$\omega_{opt} = 13.9 \%$ $\gamma_{dry} = 1.88 \text{ gr/cm}^3$	AGE OF CURING → DAYS											
	0		3		7		14		21		28	
	A	B	A	B	A	B	A	B	A	B	A	B
W_i (gr)	188.70	187.21	193.83	188.01	188.50	194.00	191.21	186.27	191.00	188.02	191.03	191.00
W_F (gr)	187.68	186.02	192.40	187.81	187.97	192.71	190.79	185.93	189.21	186.47	189.33	190.21
h_i (cm)	7.81	7.68	7.93	7.82	7.76	8.02	7.88	7.68	7.81	7.77	7.82	7.83
d (cm)	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81
A (cm ²)	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4
γ_n (gr/cm ³)	2.12	2.14	2.14	2.11	2.13	2.12	2.13	2.13	2.14	2.12	2.14	2.14
ω_i (%)	13.18	13.74	13.96	13.02	14.00	13.21	13.68	14.21	13.82	13.17	13.64	14.48
ω_F (%)	12.74	13.09	13.27	12.71	13.66	12.78	13.00	13.66	13.11	12.69	12.98	13.96
γ_d (gr/cm ³)	1.87	1.88	1.88	1.87	1.87	1.87	1.88	1.87	1.88	1.87	1.88	1.87
DIAL READING (in $\times 10^{-4}$)	128	132	352	359	501	489	569	569	600	610	628	436
P (lbs)	115	118	322	310	460	449	520	520	549	538	555	400
P (kg)	52.1	53.5	146.0	140.5	208.2	203.4	236.0	236.0	249.0	244.0	252.0	181.2
q_u (kg/cm ²)	4.57	4.70	12.8	12.3	18.3	17.8	20.7	20.7	21.8	21.4	22.1	15.9

AGE EFFECT : UNCONFINED COMPRESSIVE STRENGTHS
OF SOIL-CEMENT MIXTURES COM-
PACTED AT OPTIMUM WATER CONTENT

CEMENT CONTENT : 12 %
CURING TEMPERATURE : 21.5 °C
RELATIVE HUMIDITY : 95 %

$\omega_{opt} = 14.2 \%$ $\gamma_{dry} = 1.87 \text{ gr/cm}^3$	AGE OF CURING ——— DAYS											
	0		3		7		21		21		28	
	A	B	A	B	A	B	A	B	A	B	A	B
γ_i (gr)	189.51	187.92	188.10	187.02	191.21	194.00	183.96	181.95	191.00	188.51	194.14	188.52
γ_F (gr)	189.23	187.50	187.53	185.89	190.25	193.60	183.56	181.28	190.71	187.80	193.34	187.35
h_i (cm)	7.83	7.77	7.76	7.81	7.88	8.03	7.69	7.48	8.01	7.76	8.00	7.76
d (cm)	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.84
A (cm ²)	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4
γ_n (gr/cm ³)	2.12	2.12	2.13	2.10	2.13	2.12	2.10	2.13	2.09	2.13	2.13	2.13
ω_i (%)	13.79	14.29	14.62	12.87	13.86	13.69	12.99	13.94	12.87	13.91	14.62	13.78
ω_F (%)	13.41	13.86	14.00	12.29	13.31	13.11	12.62	13.70	12.27	13.58	14.00	13.27
γ_d (gr/cm ³)	1.87	1.86	1.86	1.86	1.87	1.87	1.86	1.87	1.86	1.87	1.86	1.87
DIAL READING ($\text{IN} \times 10^{-4}$)	92	127	264	256	430	320	630	642	686	704	676	538
P (lbs)	85	117	243	235	394	295	573	580	625	646	653	496
P (kg)	48.5	53.0	110.0	106.5	178.6	137.5	260.0	262.3	283.5	292.4	296.0	225
q_u (kg/cm ²)	4.25	4.65	9.65	9.33	15.65	11.80	22.80	23.02	24.80	25.63	26.00	19.72

OF SOIL-CEMENT SAMPLES COMPACTED
AT OPTIMUM WATER CONTENT

CEMENT CONTENT: 15 %
CURING TEMPERATURE: 21.5 °C
RELATIVE HUMIDITY: 95 %

$\omega_{opt} = 14.7 \%$ $\gamma_{dry} = 1.86 \frac{gr}{cm^3}$	AGE OF CURING ———> DAYS											
	0		3		7		14		21		28	
	A	B	A	B	A	B	A	B	A	B	A	B
W_i (gr)	185.00	196.02	186.53	185.90	190.84	188.00	188.00	182.00	192.51	186.93	190.76	187.00
W_F (gr)	183.81	194.08	185.75	—	188.90	—	187.00	181.25	191.70	185.94	186.30	185.93
h_i (cm)	7.73	8.02	7.69	7.88	7.91	7.78	7.78	7.43	8.00	7.76	7.82	7.68
d (cm)	3.81	3.81	3.81	3.84	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81
A (cm ²)	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4
γ_n (gr/cm ³)	2.10	2.14	2.19	2.09	2.11	2.11	2.12	2.15	2.11	2.11	2.14	2.14
ω_i (%)	13.27	14.83	14.48	12.67	14.76	13.36	14.56	15.69	14.78	13.49	15.79	14.83
ω_F (%)	12.81	14.16	13.96	—	13.87	—	14.05	15.11	14.25	13.02	13.00	14.31
γ_d (gr/cm ³)	1.85	1.86	1.86	1.86	1.84	1.86	1.85	1.86	1.84	1.86	1.85	1.86
DIAL READING (10×10^4)	200	211	655	632	895	909	890	915	—	—	—	—
P (lbs)	182	195	609	594	895	928	889	930	—	—	—	—
P (Kg)	82.5	88.4	276.0	269.3	405.5	420.8	404.0	421.0	442.3	413.8	459.4	446.9
q_u (Kg/cm ²)	7.24	7.75	24.2	23.6	35.6	34.0	35.4	37.0	38.8	36.3	40.3	39.2

TEMPERATURE EFFECT : UNCONFINED COMPRESSIVE STRENGTHS OF SOIL - CEMENT SAMPLES COMPACTED AT OPTIMUM WATER CONTENT

CEMENT CONTENT : 6 %
CURING TEMPERATURE : 30 °C
RELATIVE HUMIDITY : 95 %

$W_{pt} = 13.3 \%$ $Y_{dry} = 1.89 \text{ gr/cc}$	AGE OF CURING — DAYS											
	0		3		7		14		21		28	
	A	B	A	B	A	B	A	B	A	B	A	B
W_i (gr)			193.21	187.14	195.60	191.01	198.73	179.89	194.12	182.71	197.95	188.41
W_F (gr)			192.45	186.51	194.49	190.57	197.54	178.81	192.99	181.93	196.54	186.91
h_i (cm)			7.96	7.78	8.01	7.83	8.19	7.48	8.01	7.56	8.11	7.76
d (cm)			3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81
A (cm)			11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4
Y_n (gr/cc)			2.13	2.11	2.14	2.14	2.13	2.11	2.11	2.12	2.14	2.13
W_i (%)			13.04	12.86	13.28	13.47	13.09	12.79	12.91	13.00	13.39	13.21
W_F (%)			12.83	12.51	12.76	13.00	12.60	12.17	12.21	12.33	12.52	12.43
Y_d (gr/cc)			1.88	1.87	1.89	1.89	1.88	1.87	1.87	1.88	1.89	1.88
DIAL READING (10×10^4)			—	—	—	—	—	—	—	—	—	—
P (lbs)			136	143	179	128	252	245	315	316	400	412
P (kg)			61.7	64.9	81.3	58.1	114.4	111.2	143.0	143.5	181.6	187.1
q_u (kg/cm ²)			5.41	5.69	7.13	6.09	10.03	9.75	12.54	12.58	15.93	16.40

ENCLOSURE CONTAINING RESULTS
OF SOIL-CEMENT SAMPLES COM-
PACTED AT OPTIMUM WATER CONTENT

CURING TEMPERATURE: 30°C
RELATIVE HUMIDITY: 95%

$w_{opt} = 13.9\%$ $\gamma_{dry} = 1.88 \text{ gr/cm}^3$	AGE OF CURING ——— DAYS											
	0		3		7		14		21		28	
			A	B	A	B	A	B	A	B	A	B
W_i (gr)			188.89	191.75	194.75	186.73	197.16	186.97	199.80	194.92	192.36	189.56
W_F (gr)			187.99	190.75	194.00	186.27	196.17	185.89	196.87	193.54	190.99	188.03
h_i (cm)			7.82	7.86	7.99	7.69	8.16	7.81	8.12	7.99	8.04	7.77
d (cm)			3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81
A (cm ²)			11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4
γ_n (gr/cm ³)			2.12	2.14	2.14	2.13	2.12	2.10	2.16	2.14	2.10	2.14
w_i (%)			13.16	13.69	13.76	14.05	13.16	12.94	14.22	13.77	12.79	13.64
w_F (%)			12.83	13.27	13.34	13.67	12.81	12.29	13.76	13.07	12.08	12.95
γ_d (gr/cm ³)			1.87	1.88	1.88	1.87	1.87	1.86	1.87	1.88	1.86	1.88
DIAL READING (10×10^{-4})			276	288	520	260	655	689	834	876	886	894
P (lbs)			252	260	476	238	596	628	762	958	880	890
P (Kq)			114.2	118.0	216.0	108.1	270.0	285.1	346.0	434.9	398.0	404.0
q_u (kg/cm ²)			10.02	10.35	18.95	9.52	23.64	25.00	30.37	38.14	34.92	35.43

THESIS

ROBERT COLLEGE GRADUATE SCHOOL
BEBEK, ISTANBUL

TEMPERATURE EFFECT

: UNCONFINED COMPRESSIVE STRENGTHS
OF SOIL-CEMENT SAMPLES
COMPACTED AT OPTIMUM WATER
CONTENT

CEMENT CONTENT : 12 %
CURING TEMPERATURE : 30 °C
RELATIVE HUMIDITY : 95 %

$$\omega_{opt} = 14.2 \%$$

$$\gamma_{dry} = 1.87 \frac{gr}{cm^3}$$

AGE OF CURING ———> DAYS

		3		7		14		21		28	
		A	B	A	B	A	B	A	B	A	B
W _i (gr)		186.38	190.69	189.57	194.98	185.08	191.17	186.90	177.60	190.71	191.34
W _F (gr)		185.92	190.31	189.51	194.61	185.03	190.70	185.18	176.99	188.98	190.08
h _i (cm)		7.69	7.89	7.82	8.03	7.66	7.91	7.81	7.49	7.94	7.88
d (cm)		3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81
A (cm ²)		11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4
γ_n (gr/cm ³)		2.13	2.12	2.13	2.13	2.12	2.12	2.10	2.08	2.10	2.13
ω_i (%)		13.82	14.21	13.94	14.69	13.62	13.63	12.96	12.71	13.00	13.99
ω_F (%)		13.44	13.85	13.76	14.31	13.32	13.11	12.17	12.09	12.26	13.17
γ_d (gr/cm ³)		1.87	1.86	1.87	1.86	1.87	1.87	1.86	1.85	1.86	1.87
DIAL READING (10×10^{-4})		312	320	527	560	661	686	844	689	896	1023
P (lbs)		287	296	483	512	603	628	782	631	899	916
P (kg)		131.0	134.4	219.3	232.5	273.8	285.1	355.0	286.5	408.2	415.9
q _u (kg/cm ²)		11.49	11.79	19.23	20.39	24.01	25.00	31.14	25.12	37.79	36.47

THESIS

ROBERT COLLEGE GRADUATE SCHOOL
BEBEK, ISTANBUL

STRENGTHS OF SOIL-CEMENT
SAMPLES COMPACTED AT
OPTIMUM WATER CONTENT

CURING TEMPERATURE : 30°C
RELATIVE HUMIDITY : 95%

$\omega_{pt} = 14.7\%$ $\gamma_{dry} = 1.86 \frac{gr}{cm^3}$	AGE OF CURING —————> DAYS											
			3		7		14		21		28	
			A	B	A	B	A	B	A	B	A	B
W_i (gr)			185.54	190.37	180.99	179.92	181.44	184.09	176.78	195.89	189.01	193.28
W_F (gr)			184.17	189.85	180.81	181.28	186.56	183.08	—	194.24	183.28	192.36
h_i (cm)			7.61	7.84	7.60	7.48	7.72	7.69	7.59	8.03	8.81	7.96
d (cm)			3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81
A (cm ²)			11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4
γ_n (gr/cm ³)			2.14	2.13	2.09	2.11	2.13	2.10	2.07	2.14	2.10	2.13
ω_i (%)			14.79	15.71	13.45	14.78	14.52	13.41	12.67	14.83	13.29	14.48
ω_F (%)			14.17	15.56	13.43	14.31	14.00	13.02	—	14.13	12.87	14.00
γ_d (gr/cm ³)			1.86	1.84	1.84	1.86	1.86	1.85	1.85	1.86	1.85	1.86
DIAL READING (10×10^{-4})			—	—	—	—	—	—	—	—	—	—
P (lbs)			702	427	900	910	1029	1034	1100	1073	1079	979
P (kg)			319.0	194.0	409.0	413.2	467.5	470.0	500.0	488.8	490.0	445.0
q_u (kg/cm ²)			28.0	17.0	35.9	36.2	41.0	41.2	43.8	42.9	43.0	39.0

THESIS

ROBERT COLLEGE GRADUATE SCHOOL
BEBEK, ISTANBUL

PAGE 61

Effect of Density: 0-day Unconfined Compressive Strengths of
Soil-Cement Samples Compacted at optimum
Water Content.

Curing Temperature : 21.5°C

Relative Humidity : 95 %

Compactive Effort : 15/20 Blows per layer [⊗]

	Cement Content (on dry soil weight basis)							
	6 %		9 %		12 %		15 %	
	15	20	15	20	15	20	15	20
W_1 (gr)	186.41	187.00	181.00	185.92	206.73	179.10	209.50	181.00
W_f (gr)	—	—	—	—	—	—	—	—
h_1 (cm)	7.99	7.81	7.67	7.76	8.67	7.53	8.77	7.53
d (cm)	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81
A (cm ²)	11.40	11.40	11.40	11.40	11.40	11.40	11.40	11.40
γ_n (gr/cm ³)	2.05	2.10	2.06	2.10	2.09	2.09	2.09	2.09
w_1 (%)	13.33	13.59	14.00	14.10	14.67	14.23	14.31	14.60
w_f (%)	—	—	—	—	—	—	—	—
γ_d (gr/cm ³)	1.81	1.85	1.80	1.84	1.82	1.83	1.83	1.84
R (in x 10 ⁻⁴)	—	—	—	—	—	—	—	—
P(lb)	91.50	95.2	101.2	105.0	102.6	105.0	141.0	155.2
P(kg)	41.6	43.4	46.1	47.9	46.7	47.9	64.0	70.6
q_u (kg/cm ²)	3.65	3.81	4.05	4.20	4.10	4.20	5.61	6.20

⊗ 5.5 lb-hammer, 3 layers, 12"-drop

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ROBERT COLLEGE GRADUATE SCHOOL
BEBEK, ISTANBUL

PAGE 62

Effect of Density: 0-day Compressive Strengths of Soil-Cement Samples Compacted at Optimum Water Content

Curing Temperature : 21.5°C

Relative Humidity : 95 %

Compactive Effort : 35/30 Blows per layer[⊗]

	Cement Content (on dry soil weight basis)							
	6 %		9 %		12 %		15 %	
	35	30	35	30	35	30	35	30
W_1 (gr)	182.00	180.00	201.50	200.83	197.35	196.50	197.80	191.62
W_f (gr)	—	—	—	—	—	—	—	—
h_1 (cm)	7.32	7.29	8.09	8.00	8.05	7.96	8.00	7.83
d (cm)	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81
A (cm ²)	11.40	11.40	11.40	11.40	11.40	11.40	11.40	11.40
γ_n (gr/cm ³)	2.18	2.17	2.18	2.18	2.15	2.16	2.17	2.15
w_1 (%)	13.26	13.61	14.33	14.43	14.18	14.07	14.89	14.60
w_f (%)	—	—	—	—	—	—	—	—
γ_d (gr/cm ³)	1.92	1.91	1.91	1.90	1.89	1.88	1.89	1.88
R (in $\times 10^{-4}$)	248	—	256	—	272	—	284	—
P (lb)	225.0	175.7	235.0	166.0	249.0	140.0	266.0	240.8
P (kg)	102.0	79.9	106.6	75.5	112.9	63.6	120.7	109.6
q_u (kg/cm ²)	8.95	7.01	9.08	6.62	9.90	5.59	10.58	9.64

⊗ 5.5 lb hammer, 3 layers 12"-drop.

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ROBERT COLLEGE GRADUATE SCHOOL
BEBEK, ISTANBUL

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Effect of Density: 7-day Unconfined Compressive Strengths of Soil Cement Samples Compacted at Optimum Water Content

Curing Temperature : 21.5°C

Relative Humidity : 95 %

Compactive Effort : 15/20 blows per layer

	Cement Content (on dry soil weight basis)							
	6 %		9 %		12 %		15 %	
	15	20	15	20	15	20	15	20
W_i (gr)	183.60	190.80	180.09	186.00	182.50	191.00	186.00	178.30
W_f (gr)	—	189.89	179.87	185.93	181.47	190.24	—	177.58
h_i (cm)	7.82	7.91	7.69	7.80	7.77	8.00	7.88	7.45
d (cm)	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81
A (cm ²)	11.40	11.40	11.40	11.40	11.40	11.40	11.40	11.40
γ_n (gr/cm ³)	2.06	2.11	2.06	2.10	2.06	2.09	2.07	2.10
w_i (%)	13.47	14.76	13.69	13.90	14.29	14.48	14.96	15.30
w_f (%)	—	14.51	13.39	13.67	13.87	14.00	—	14.90
γ_d (gr/cm ³)	1.82	1.84	1.81	1.84	1.80	1.83	1.80	1.82
R (in $\times 10^{-4}$)	—	—	—	—	—	—	—	—
P (lb)	—	—	—	—	—	—	—	—
P (kg)	44.4	45.1	185.0	191.9	159.8	164.3	247.2	318.1
q_u (kg/cm ²)	3.89	3.95	16.2	16.8	14.0	14.4	21.66	27.9

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ROBERT COLLEGE GRADUATE SCHOOL
BEBEK, ISTANBUL

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Effect of Density: 7-day Unconfined Compressive Strengths of
Soil-cement Samples Compacted at Optimum
Water Content.

Curing Temperature : 21.5°C

Relative Humidity : 95 %

Compactive Effort : 35/30 Blows per layer[≡]

	Cement Content (on dry soil weight basis)							
	6 %		9 %		12 %		15 %	
	35	30	35	30	35	30	35	30
W_1 (gr)	195.50	188.20	199.70	198.00	191.00	192.70	189.00	188.8
W_f (gr)	195.48	186.75	199.17	—	—	192.3	187.91	—
h_1 (cm)	7.80	7.56	7.96	8.00	7.68	7.83	7.49	7.66
d (cm)	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81
A (cm ²)	11.40	11.40	11.40	11.40	11.40	11.40	11.40	11.40
γ_n (gr/cm ³)	2.20	2.18	2.20	2.17	2.18	2.16	2.21	2.16
w_1 (%)	13.62	13.09	13.99	13.80	14.31	14.48	15.03	14.89
w_f (%)	13.48	12.87	13.76	—	—	14.07	14.79	—
γ_d (gr/cm ³)	1.94	1.92	1.93	1.91	1.91	1.89	1.92	1.88
R (in x 10 ⁻⁴)	498		808		798		998	
P (lb)	455	306	735	625	729	539	1120	1069
P (kg)	206.0	139.0	333.0	284.0	330.0	245.0	519.0	486.0
q_n (kg/cm ²)	18.1	12.2	29.2	24.9	29.0	21.5	45.5	42.6

≡ 5.5 lb hammer, 3 layers, 12"-drop.

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ROBERT COLLEGE GRADUATE SCHOOL
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Effect of water content : 0- day and 7- day unconfined
compressive strengths of soil - ce-
ment samples compacted on dry
side of optimum water content

Curing Temperature : 21.5° C

Relative Humidity : 95%

Compacted Effort : 25 Blows per layer*

	CEMENT CONTENT (on dry soil weight basis)							
	6 %		9 %		12 %		15 %	
	0-DAY	7-DAY	0-DAY	7-DAY	0-DAY	7-DAY	0-DAY	7-DAY
W _i (gr)	168.33	195.00	165.96	159.40	177.03	179.26	159.32	187.45
W _p (gr)	—	192.52	—	159.16	—	178.36	—	186.30
h _i (cm)	7.61	8.67	7.36	7.12	7.81	8.02	7.12	8.36
d (cm)	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81
A (cm ²)	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4
Y _n (gr/cm ³)	1.94	1.97	1.97	1.96	1.99	1.96	1.97	1.96
W _i (%)	9.13	9.09	9.35	9.15	9.41	9.26	9.03	8.83
W _p (%)	—	8.83	—	8.95	—	9.00	—	8.61
Y _d (gr/cm ³)	1.77	1.79	1.80	1.80	1.82	1.79	1.80	1.80
READING (IN x 10 ⁴)	53	—	65	265	76	292	89	343
P (lbs)	45	65.4	60	240	71	268	80	315
P (kg)	20.4	29.7	27.2	108.9	32.2	123.1	36.3	142.8
q _u (kg/cm ²)	1.79	2.60	2.38	9.55	2.82	10.81	3.18	12.51

* - 5.5 lb-hammer
3 layers
12" - drop

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ROBERT COLLEGE GRADUATE SCHOOL
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Effect of water content : 0- day unconfined compressive strengths of soil - cement samples compacted on wet side of optimum water content

Curing Temperature : 21.5° C

Relative Humidity : 95%

Compactive Effort : 25 Blows per layer*

	CEMENT CONTENT (on dry soil weight basis)							
	6 %		9 %		12 %		15 %	
	A	B	A	B	A	B	A	B
W _i (gr)	188.20	189.90	186.90	192.00	189.91	195.00	181.52	195.81
W _F (gr)	—	—	—	—	—	—	—	—
h _i (cm)	7.73	7.91	7.76	7.88	7.91	8.00	7.49	8.04
d (cm)	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81
A (cm ²)	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4
Y _n (gr/cm ³)	2.14	2.14	2.14	2.14	2.14	2.15	2.14	2.13
W _i (%)	14.96	16.78	15.43	17.38	16.28	18.93	17.05	19.28
W _F (%)	—	—	—	—	—	—	—	—
Y _d (gr/cm ³)	1.86	1.83	1.85	1.82	1.84	1.81	1.83	1.79
READING (INX10)	128	118	136	112	150	130	229	181
P (lbs)	117	94	123	105	138	120	209	165
P (kg)	53.1	34.0	55.9	47.6	63.5	54.5	94.9	74.9
Q _u (kg/cm ²)	4.66	2.98	4.90	4.18	5.56	4.78	8.31	6.56

* - 5.5-lb hammer
3 layers
12" - drop

Effect of water content :

7. day unconfined compressive strengths of soil - cement samples compacted on wet side of optimum water content

Curing Temperature: 21.5°C

Relative Humidity : 95%

Compactive Effort : 25 Blows per layer*

	CEMENT CONTENT (on dry soil weight basis)							
	6 %		9 %		12 %		15 %	
	A	B	A	B	A	B	A	B
W _i (gr)	187.25	187.40	182.10	186.68	193.60	191.00	192.00	186.52
W _F (gr)	185.93	186.73	181.19	185.90	193.14	190.72	191.09	186.38
h _i (cm)	7.68	7.72	7.48	7.66	7.94	7.82	7.88	7.66
d (cm)	3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81
A (cm ²)	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4
γ _n (gr/cm ³)	2.14	2.13	2.14	2.14	2.14	2.14	2.14	2.15
w _i (%)	14.87	16.69	15.38	17.73	16.42	18.81	16.99	19.08
w _F (%)	14.28	15.96	14.87	17.00	15.98	18.21	16.29	18.65
γ _d (gr/cm ³)	1.86	1.83	1.85	1.82	1.84	1.81	1.83	1.80
READING (10x10 ⁴)	142	112	526	440	552	393	894	888
P (lbs)	131	102	479	402	503	362	902	786
P (kg)	59.5	46.3	217.0	182.0	228.0	164.1	409.0	356.1
q _u (kg/cm ²)	5.22	4.06	19.02	15.96	20.00	14.40	35.81	31.21

* - 5.5 - lb hammer
3 layers
12" - drop

B. Results and Discussions

The Effect of Cement Content On Consistency Indices:

When six, nine, 12 and 15 per cents of cement by dry weight was added to the soil, the changes on the Atterberg Limits (LL, PL, PI) of soil were found out. The flow curves were drawn. The results are given on pages (34-36). As it is shown by the curves on page (98), the liquid and plastic limits show an increase with the cement content until around 9 per cents of the cement content. Plasticity index curve which is the difference of liquid and plastic limit curves, starts to decrease smoothly after a cement content of 6 per cent. The increase of liquid and plastic limits with the cement content may be because of the flocculation of cement particles around soil, preventing the structure from dispersion.

Effect of Cement Content on Soil-Cement Compaction Characteristics:

To find the effect of cement content on the compaction characteristics of the soil, proctor curves were plotted for soil containing 0, 6, 9, 12, 15 per cents of cement. The variation of optimum moisture content and maximum dry density with the cement content are given on the page (97). As it is seen from these curves, there is a slight increase in optimum water content, and a slight decrease in maximum dry density. The variations being a maximum of 1.6 per cent and 0.03 gr/cubic centimeters respectively.

Therefore, as the cement content increases, more water becomes necessary to bring the moisture level to the optimum level, which shows the necessity of additional water for cement particles. As a result of this, the maximum dry density is reached at lower levels.

Wetting-Drying Tests:

The results showing the variation of soil-cement losses by cement content and dry density are given on page (91). These values were also plotted on pages (99-100). From these graphs it is seen that there is a sharp decrease in the soil-cement loss as the cement content and dry density increase. The total disintegration of the samples containing six per cents of cement is an indication of the prominent role the cement content plays. As the cement content increases, the binding properties of cement increases, preventing the material from loosening. As the density increases, soil and cement particles come in close contact. The cementation starts, and resistance to the outside forces increases because of this close contact and cementation, as a result of densification.

Freezing and Thawing Tests:

The pattern of length-changes with freezing and thawing cycles are shown on pages (101-102). From these curves it is seen that all samples are increased in length. The disintegration of samples stabilized with six per cent cement, without completing the 12 cycles show

that volume (length)-change and moisture change characteristics of the specimens depend a great deal on the cement content.

The soil-cement losses occurred during the freezing and thawing cycles are shown on page (94). The variation of soil-cement losses with cement content were plotted on page (99). The loss with 12 per cent cement sample deviated much from the trend. This was mainly because of the considerable amount of water absorbed during the thawing period, resulting in loosening of the sample. As it is seen in the graph, the trend is that soil-cement losses decrease as cement content increases.

Unconfined Compression Tests for Soil:

The soil samples without cement in them were tested for compressive strength at optimum water content compacted under different loads. Also the samples were compacted at above and below the optimum water content and tested to make comparisons later with soil-cement samples when searching for the effect of water content.

Effect of Cement Content:

The relation between cement content and unconfined compression strength at room temperatures, and at different curing times, were plotted on page (103). As the cement content increases, the unconfined compressive strength decreases, too. The rate of increase at different

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curing times shows a distinct variation, the rate being the lowest for zero days and maximum for 14 days.

This increase of the compressive strength with the cement content may be because of the cementation of soil and cement particles giving rise to a hard and coherent mass, the hardness and coherence being proportional to the cement content.

Effect of Age (Curing Time):

The variations of the unconfined compressive strength with the curing time were plotted on page (104). As the graph shows, the strength of all cement stabilized specimens are several times greater than the strength of the nonstabilized soils. Therefore, curing in a moist atmosphere may cause the cementation reactions between soil and cement to proceed. The rate of increase of all cement-stabilized soil samples except those with six per cent cement content, tend to be constant towards 28 days.

Effect of Temperature:

The variation of unconfined compressive strengths with temperature were plotted on pages (105-106). The results show an increase in compressive strength with temperature. This trend of increase in strength may reveal that the cementation reactions are accelerated at high temperatures.

Effect of Density:

The variation of density obtained by compacting the samples at different energies, (that is, layers taking 15, 20, 25, 30, 35 blows). The changes of compressive strengths with density were plotted on pages (107-110). All graphs show that as density increases, compressive strength increases, too. As explained before, the densification of soil results in closeness of cement and soil particles by decreasing the void ratio and gives rise to easy cementation.

Effect of Water Content:

The relationship between water content and compressive strength shows a constant trend as given on pages (111-112). The maximum compressive strengths were obtained on the wet side of optimum in almost all samples. All the samples compacted on the dry side of optimum water content resulted in lower compressive strengths both at zero-days and seven-day strengths. The strengths also decreases after two per cent points of the optimum. In this case, the rate of strain was very high.

The lower strngths obtained on the dry side of the optimum water content may be an indication that the necessary amount of water for the cementation reactions to proceed properly, is lacking. Therefore, hardness and coherence of the structure cannot be obtained, and this results in low compressive strength.

The water content very much above the optimum may cause low compressive strength. Because in this case, the media between soil and cement particles, soil and soil particles, and finally among the cement particles are diluted and this may prevent binding and cementation.

C. Conclusions

A series of compaction tests were performed for soil and soil-cement mixtures, containing zero, six, nine, 12 and 15 per cents of cement on dry weight basis of soil. These test results were used to determine the moisture content to be employed in making specimens for compressive strength testing. At the end of these tests, it was observed that the maximum dry density decreases slightly and the optimum moisture content increases as cement content increases.

The compressive strength tests which were performed to determine the effect of curing time (age effect), curing temperature, molding water content, and density helped in specifying the minimum cement content to be used for this soil at a given age, temperature, water content and density respectively.

The results of these different factors affecting the soil-cement may be evaluated and utilized in practice in the following way:

Like in the concrete technology, soil cement gains strength with time. Therefore a yield of the probable strength in actual construction at any time can be guessed by performing proper tests in the laboratory.

The second important results obtained is that soil at least does not interfere with the hydration of cement.

It was observed that at elevated temperatures, the strength of soil-cement increases. The rate of increase of strength for 28-day strength, for the soil stabilized with 12 per cent of cement is about one kilogram per square centimeter per degree Centigrade. This result may be utilized in slightly conservative estimates of probable cement content in summer and generally in hot climates.

Also it was found out that if soil-cement samples are compacted on slightly wet side of optimum water content, maximum structural strength and best workability is obtained. The use of this result of soils having natural water contents slightly above the optimum water content in actual mixing operation is obvious.

The increase of compressive strength of the soil-cement samples with dry density is a recognition of the fact that moisture-density relations for soils are valid also for soil-cement samples. This result is also an indication of the fact that "densification" which is the result of compaction, is the essential base of stabilization.

Durability tests composed of repetitional wetting-drying and freezing -thawing tests were performed to find out the suitability of the soil, TOPSER-RED, for use under particularly severe climatic conditions as well as to determine for this soil the minimum amount of cement needed to hold the mass together and maintain stability under

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the shrinkage and expansive forces which occur in nature. The results obtained effectively serve to evaluate the above points.

Finally, the results of the plasticity tests were found out to be useful to determine the mixing easiness of soil and cement in the field. The interval in which the plasticity index of soil-cement tended to increase may be an indication of workability, with a suggestion of using less amount of cement than the required.

To come to a conclusion at the end of this set of experiments, in the light of above discussion, the following table²¹ and the requirements of Portland Cement Association were considered as a guide.

Soil Type	P.R.Classification	A ₆ , A ₇
	Casagrande Classification	ML, CI, CL, CH
Effect of Cement: shows substantial hardening		—
Minimum acceptable compressive strength		250 lb/in ²
Maximum allowable volume change in durability tests		2 %
Maximum allowable loss of weight in durability tests		7 %
Normal cement content		10-14 %

21. Soil Mechanics for Road Engineers, Department of Scientific and Industrial Research, Road Laboratory, London, 1957, p.249.

By comparing the maximum volume changes in durability tests, and maximum soil-cement loss and minimum compressive strength with the allowable values in the above table, soil used for investigation may be stabilized with a cement content between 12 per cent and 15 per cent.

Therefore, the soil used (TOPSER-RED) when mixed and properly stabilized with 14 per cent of cement might be used as:

- (a) sub-bases for major roads (for light traffic);
- (b) surfacing for minor roads;
- (c) airfields;
- (d) military roads;
- (e) footpaths, car parks, shipyards, and so on.

Conducting a study by taking the type, structure and gradation of soil, and duration of mixing as a parameter to the understanding of the nature and mechanism of soil-cement interactions.

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SYMBOLS USED

- W_i = Initial weight of sample
- W_f = Final weight of sample
- h_i = height of sample
- d = diameter of sample
- A = Area of sample
- γ_n = Wet unit weight of sample
- γ_d = Dry unit weight of sample
- w_i = Initial water content of sample
- w_f = Final water content of sample
- R = Dial reading
- P = Load on sample at failure
- q_u = Unconfined compressive strength
- $LL (w_L)$ = Liquid limit
- $PL (w_P)$ = Plastic limit
- $PI (I_p)$ = Plasticity index

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A. Calculations

The Results of Soil and Soil-Cement Compaction Tests

Cement Content (%)	Dry Density (gr/cm ³)	Water Content (%)	Maximum Dry Density (gr/cm ³)	Optimum Water Content (%)
0	1.73	5.8	1.89	13.1
	1.88	11.3		
	1.88	15.4		
	1.83	19.0		
	1.64	21.2		
	1.58	22.3		
6	1.67	3.6	1.89	13.3
	1.79	7.1		
	1.88	12.3		
	1.88	16.4		
	1.76	21.9		
	1.65	24.6		
9	1.71	6.8	1.88	13.9
	1.80	8.3		
	1.86	12.3		
	1.87	16.7		
	1.72	22.6		
	1.60	27.3		
12	1.70	6.9	1.87	14.2
	1.82	9.0		
	1.87	14.2		
	1.84	18.4		
	1.71	21.8		
	1.66	22.1		
15	1.67	5.9	1.86	14.7
	1.76	8.8		
	1.84	12.1		
	1.86	14.6		
	1.81	18.6		
	1.70	22.7		

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UNCONFINED COMPRESSIVE STRENGTH OF THE SOIL *

A. At optimum water content

15 BLOWS PER LAYER			25 BLOWS PER LAYER			35 BLOWS PER LAYER		
w (%)	γ_d (gr/cm ³)	q_u (kg/cm ²)	w (%)	γ_d (gr/cm ³)	q_u (kg/cm ²)	w (%)	γ_d (gr/cm ³)	q_u (kg/cm ²)
13.18	1.86	4.03	12.83	1.87	4.33	13.21	1.92	5.26
13.00	1.86	3.79	12.96	1.86	4.26	13.27	1.91	5.67
12.91	1.85	3.46	13.17	1.88	4.45	13.18	1.93	5.93
13.31	1.87	4.41	13.23	1.89	4.96	13.15	1.94	6.34
13.18	1.86	4.00	13.16	1.88	4.37	13.36	1.92	6.12
12.92	1.85	3.75	13.21	1.89	5.17	13.15	1.93	5.87
MEAN $q_u \rightarrow$		3.92	MEAN $q_u \rightarrow$		4.70	MEAN $q_u \rightarrow$		5.85

B. Below optimum water content

w (%)	γ_d (gr/cm ³)	q_u (kg/cm ²)
9.23	1.81	3.87
10.00	1.84	4.00
9.43	1.83	3.98
10.23	1.84	4.18
9.47	1.83	3.96
9.18	1.82	3.76
MEAN $q_u \rightarrow$		3.95

C. Above optimum water content

w (%)	γ_d (gr/cm ³)	q_u (kg/cm ²)
21.9	1.74	2.76
22.3	1.71	2.31
19.8	1.76	3.18
21.6	1.75	2.86
21.2	1.77	3.23
19.3	1.81	3.36
MEAN $q_u \rightarrow$		2.94

* TESTS WERE PERFORMED ON THE SPECIMENS OBTAINED FROM PROCTOR MOLD, UNDER GIVEN COMPACTIVE ENERGIES AND WATER CONTENTS

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Wetting-Drying Tests

Soil-Cement Loss Calculations:

Soil-cement losses were calculated as follows:

$$\text{Soil-cement Loss (\%)} = \frac{(W_o - W_c) \times 100}{W_o}$$

where,

W_o = original calculated oven dry weight (gr)

W_c = corrected oven dry weight after 12 cycles at 110°C given by:

$$W_c = \frac{W_{110}}{W_R} \times 100 \quad (100)$$

where,

W_{110} = Oven dry weight after drying at 110°C

W_R = per cent of water retained in specimen.

Per cent water retained because of hydration of water is given in the following table according to various soil groups.²²

AASHTO SOIL CLASSIFICATION	PERCENT WATER RETAINED AFTER DRYING AT 110°C
A-1 , A-3	1.5
A-2	2.5
A-4	3.0
A-6 , A-7	3.5

22. Oven-dry weight of specimen No.2 was corrected since some water had reacted with the cement and the soil during the test, and was retained in the specimen when dried to constant weight at 110°C.
23. ASTM Designation D559 "Standard Method of Wetting and Drying Tests of Compacted Soil-Cement Mixtures."

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WETTING - DRYING SOIL-CEMENT LOSS CALCULATIONS VARIATION WITH DRY DENSITY

9% *

$W_n = 1962 \text{ gr}$, $W_{110} = 1153 \text{ gr}$	$W_n = 1981 \text{ gr}$, $W_{110} = 1228 \text{ gr}$
$W_o = \frac{1962 \times 100}{100 + 13.96} = 1727 \text{ gr}$	$W_o = \frac{1981 \times 100}{100 + 13.8} = 1742 \text{ gr}$
$W_c = \frac{1153 \times 100}{100 + 3.50} = 1113 \text{ gr}$	$W_c = \frac{1228 \times 100}{100 + 3.50} = 1187 \text{ gr}$
$Loss = \frac{(1727 - 1113) 100}{1727} = 35.5 \%$	$Loss = \frac{(1742 - 1187) 100}{1742} = 31.9 \%$
$W_n = 2039$, $W_{110} = 1390$	$W_n = 2024$, $W_{110} = 1349$
$W_o = \frac{2039 \times 100}{100 + 13.88} = 1870 \text{ gr}$	$W_o = \frac{2024 \times 100}{100 + 13.57} = 1785 \text{ gr}$
$W_c = \frac{1390 \times 100}{100 + 3.50} = 1343 \text{ gr}$	$W_c = \frac{1349 \times 100}{100 + 3.50} = 1302 \text{ gr}$
$Loss = \frac{(1870 - 1343) 100}{1870} = 28.2 \%$	$Loss = \frac{(1785 - 1302) 100}{1785} = 27.0 \%$
$W_n = 2076$, $W_{110} = 1548$	$W_n = 2080$, $W_{110} = 1478$
$W_o = \frac{2076 \times 100}{100 + 13.96} = 1998 \text{ gr}$	$W_o = \frac{2080 \times 100}{100 + 13.68} = 1833 \text{ gr}$
$W_c = \frac{1548 \times 100}{100 + 3.50} = 1496 \text{ gr}$	$W_c = \frac{1478 \times 100}{100 + 3.50} = 1426 \text{ gr}$
$Loss = \frac{(1998 - 1496) 100}{1998} = 25.1 \%$	$Loss = \frac{(1833 - 1426) 100}{1833} = 22.2 \%$

* - SOIL-CEMENT SAMPLES CONTAINING 6% CEMENT WERE DISINTEGRATED IN WATER

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WETTING - DRYING SOIL - CEMENT LOSS CALCULATIONS VARIATION WITH DRY DENSITY

12 %

$W_n = 1979$, $W_{110} = 1292$	$W_n = 2015$ $W_{110} = 1400$
$W_o = \frac{1979 \times 100}{100 + 14.25} = 1731 \text{ gr}$	$W_o = \frac{2015 \times 100}{100 + 14.36} = 1762 \text{ gr}$
$W_c = \frac{1292 \times 100}{100 + 3.50} = 1249 \text{ gr}$	$W_c = \frac{1400 \times 100}{100 + 3.50} = 1351 \text{ gr}$
$Loss = \frac{(1731 - 1249)100}{1731} = 27.9 \%$	$Loss = \frac{(1762 - 1351)100}{1762} = \%$
$W_n = 2041$, $W_{110} = 1516$	$W_n = 2038$ $W_{110} = 1527$
$W_o = \frac{2041 \times 100}{100 + 14.4} = 1784 \text{ gr}$	$W_o = \frac{2038 \times 100}{100 + 14.10} = 1784 \text{ gr}$
$W_c = \frac{1516 \times 100}{100 + 3.50} = 1463 \text{ gr}$	$W_c = \frac{1527 \times 100}{100 + 3.50} = 1461 \text{ gr}$
$Loss = \frac{(1784 - 1463)100}{1784} = 18.0 \%$	$Loss = \frac{(1784 - 1461)100}{1784} = 18.1 \%$
$W_n = 2069$, $W_{110} = 1637$	$W_n = 2091$, $W_{110} = 1621$
$W_o = \frac{2069 \times 100}{100 + 14.80} = 1984 \text{ gr}$	$W_o = \frac{2091 \times 100}{100 + 14.31} = 1827 \text{ gr}$
$W_c = \frac{1637 \times 100}{100 + 3.50} = 1581 \text{ gr}$	$W_c = \frac{1621 \times 100}{100 + 3.50} = 1568 \text{ gr}$
$Loss = \frac{(1984 - 1581)100}{1984} = 20.3 \%$	$Loss = \frac{(1827 - 1568)100}{1827} = 14.3 \%$

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WETTING - DRYING SOIL - CEMENT LOSS CALCULATIONS VARIATION WITH DRY DENSITY

15 %

$W_n = 1978$, $W_{110} = 1491$	$W_n = 2008$, $W_{110} = 1681$
$W_o = \frac{1978 \times 100}{100 + 14.96} = 1723 \text{ gr}$	$W_o = \frac{2008 \times 100}{100 + 15.30} = 1741 \text{ gr}$
$W_c = \frac{1491 \times 100}{100 + 3.50} = 1442 \text{ gr}$	$W_c = \frac{1681 \times 100}{100 + 3.50} = 1536 \text{ gr}$
$Loss = \frac{(1723 - 1442) 100}{1723} = 16.5 \%$	$Loss = \frac{(1741 - 1536) 100}{1741} = 11.8 \%$
$W_n = 2017$ $W_{110} = 1698$	$W_n = 2038$ $W_{110} = 1669$
$W_o = \frac{2017 \times 100}{100 + 14.40} = 1760 \text{ gr}$	$W_o = \frac{2038 \times 100}{100 + 14.86} = 1772 \text{ gr}$
$W_c = \frac{1698 \times 100}{100 + 3.50} = 1640 \text{ gr}$	$W_c = \frac{1689 \times 100}{100 + 3.50} = 1632 \text{ gr}$
$Loss = \frac{(1760 - 1640) 100}{1760} = 6.8 \%$	$Loss = \frac{(1772 - 1632) 100}{1772} = 7.9 \%$
$W_n = 2058$, $W_{110} = 1752$	$W_n = 2074$ $W_{110} = 1791$
$W_o = \frac{2058 \times 100}{100 + 14.50} = 1795 \text{ gr}$	$W_o = \frac{2074 \times 100}{100 + 14.73} = 1809 \text{ gr}$
$W_c = \frac{1752 \times 100}{100 + 3.50} = 1692 \text{ gr}$	$W_c = \frac{1791 \times 100}{100 + 3.50} = 1731 \text{ gr}$
$Loss = \frac{(1795 - 1692) 100}{1795} = 5.74 \%$	$Loss = \frac{(1809 - 1731) 100}{1809} = 4.3 \%$

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FREEZE - THAW

SOIL - CEMENT LOSS CALCULATIONS

6 %	SAMPLE A	6 %	SAMPLE B
$\gamma_d = 1.87$ $\gamma_n = 2.12$ $\omega = 13.5$	$W_n = 2034$ $W_{110} = 1698$	$\gamma_d = 1.88$ $\gamma_n = 2.12$ $\omega = 12.98$	$W_n = 2028$ $W_{110} = 1718$
$W_o = \frac{2034 \times 100}{100 + 13.5} = 1792 \text{ gr}$		$W_o = \frac{2028 \times 100}{100 + 12.98} = 1797 \text{ gr}$	
$W_c = \frac{1698 \times 100}{100 + 3.50} = 1640 \text{ gr}$		$W_c = \frac{1718 \times 100}{100 + 3.50} = 1649 \text{ gr}$	
$\text{SOIL - CEMENT LOSS (\%)} = \frac{(1792 - 1640) 100}{1792}$ $= 8.80$		$\text{SOIL - CEMENT LOSS (\%)} = \frac{(1797 - 1649) 100}{1797}$ $= 8.24$	
9 %	SAMPLE A	9 %	SAMPLE B
$\gamma_d = 1.88$ $\gamma_n = 2.14$ $\omega = 13.90$	$W_n = 2048$ $W_{110} = 1696$	$\gamma_d = 1.86$ $\gamma_n = 2.11$ $\omega = 13.67$	$W_n = 2017$ $W_{110} = 1703$
$W_o = \frac{2048 \times 100}{100 + 13.90} = 1800 \text{ gr}$		$W_o = \frac{2017 \times 100}{100 + 13.67} = 1773 \text{ gr}$	
$W_c = \frac{1696 \times 100}{100 + 3.50} = 1639 \text{ gr}$		$W_c = \frac{1703 \times 100}{100 + 3.50} = 1646 \text{ gr}$	
$\text{SOIL - CEMENT LOSS (\%)} = \frac{(1800 - 1639) 100}{1800}$ $= 8.95$		$\text{SOIL - CEMENT LOSS (\%)} = \frac{(1773 - 1646) 100}{1773}$ $= 7.16$	

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FREEZE - THAW

SOIL - CEMENT LOSS CALCULATIONS

12 %	SAMPLE A	12 %	SAMPLE B
$\gamma_d = 1.87$ $\gamma_n = 2.14$ $\omega = 13.96$	$W_n = 2043$ $W_{110} = 1555$	$\gamma_d = 1.86$ $\gamma_n = 2.13$ $\omega = 14.40$	$W_n = 2026$ $W_{110} = 1505$
$W_o = \frac{2043 \times 100}{100 + 13.96} = 1797 \text{ gr}$		$W_o = \frac{2026 \times 100}{100 + 14.40} = 1771 \text{ gr}$	
$W_c = \frac{1555 \times 100}{100 + 3.50} = 1500 \text{ gr}$		$W_c = \frac{1505 \times 100}{100 + 3.50} = 1453 \text{ gr}$	
$\text{SOIL - CEMENT LOSS (\%)} = \frac{(1797 - 1500) 100}{1797}$ $= 16.50$		$\text{SOIL - CEMENT LOSS (\%)} = \frac{(1771 - 1453) 100}{1771}$ $= 17.90$	
15 %	SAMPLE A	15 %	SAMPLE B
$\gamma_d = 1.85$ $\gamma_n = 2.10$ $\omega = 14.96$	$W_n = 2040$ $W_{110} = 1756$	$\gamma_d = 1.86$ $\gamma_n = 2.13$ $\omega = 14.73$	$W_n = 2024$ $W_{110} = 1719$
$W_o = \frac{2040 \times 100}{100 + 14.96} = 1776 \text{ gr}$		$W_o = \frac{2024 \times 100}{100 + 14.73} = 1770 \text{ gr}$	
$W_c = \frac{1756 \times 100}{100 + 3.50} = 1695 \text{ gr}$		$W_c = \frac{1719 \times 100}{100 + 3.50} = 1659 \text{ gr}$	
$\text{SOIL - CEMENT LOSS (\%)} = \frac{(1776 - 1695) 100}{1776}$ $= 4.56$		$\text{SOIL - CEMENT LOSS (\%)} = \frac{(1770 - 1659) 100}{1776}$ $= 6.25$	

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FREEZE - THAW TEST RESULTS

VOLUME AND MOISTURE CHANGE

6%

FREEZE - THAW CYCLES	UNIT LENGTH (VOLUME) CHANGE (cm/cm)				MOISTURE CHANGE	
	SAMPLE A		SAMPLE B		SAMPLE A (%)	SAMPLE B (%)
	FREEZE	THAW	FREEZE	THAW		
1	.0017	.0051	.0068	.0136	3.34	3.30
2	.0043	.0102	.0110	.0221	3.54	3.90
3	.0085	.0221	.0145	.0298	3.29	4.70
4	.0145	.0289	.0204	.0349	4.14	4.00
5	.0264	.0340	—	—	3.54	—
6	*		**			
7						
8						
9						
10						
11						
12						

* - SAMPLES FAILED AFTER 5 CYCLES
**- " " " 4 "

Max. Volume (length) change : 3.49 %

Max. Moisture change : 4.70 % (After 4 cycles)

Sample calculation for volume (length) change :

Cycle No : 4
Sample : B
Original Length of sample $l_0 = 11.76$ cm
Length of sample at 4th cycle $l_4 = 12.17$ cm
Volume (length) change = $\frac{(l_4 - l_0)100}{l_0}$
= $\frac{(12.17 - 11.76)100}{11.76}$
= 3.49 %

Sample calculation for moisture change :

Cycle No : 1 , W = 2038 gr
sample : A w% = 13.36
Original oven dry wt = $\frac{2038 \times 100}{100 + 13.36} = 1794$
Moisture content = $\left(\frac{2093}{1794} - 1 \right) \times 100$
(cycle 1) = 16.70 %
∴ Moisture change = 16.70 - 13.36 = 3.34 %

FREEZE - THAW TEST RESULTS

VOLUME AND MOISTURE CHANGE

9%

FREEZE- THAW CYCLES	UNIT LENGTH (VOLUME) CHANGE (cm/cm)				MOISTURE CHANGE	
	SAMPLE A		SAMPLE B		SAMPLE A (%)	SAMPLE B (%)
	FREEZE	THAW	FREEZE	THAW		
1	.00170	.0051	.0034	.0068	4.1	1.7
2	.0043	.0069	.0059	.0077	6.1	2.9
3	.0085	.0144	.0077	.0110	5.5	3.7
4	.0077	.0119	.0085	.0093	5.6	3.5
5	.0136	.0170	.0128	.0153	5.3	4.0
6	.0153	.0221	.0111	.0161	5.7	4.5
7	.0145	.0204	.0136	.0179	5.4	3.8
8	.0145	.0230	.0179	.0204	6.2	3.4
9	.0170	.0221	.0170	.0221	5.9	3.2
10	.0221	.0238	.0187	.0247	6.1	3.0
11	.0229	.0272	.0238	.0236	6.0	4.6
12	.0246	.0325	.0247	.0264	6.0	2.9

Max. volume (length) change : 3.23 %

Max. Moisture change : 9.60 %

Sample calculation for volume (length) change :

cycle No : 12
Sample : B
Original length of sample $l_0 = 11.77$ cm
Length of sample at 12th cycle $l_{12} = 12.15$ cm
 $\therefore$ Volume (length) change = $\frac{(l_{12} - l_0) 100}{l_0}$
 $= \frac{(12.15 - 11.77) 100}{11.77}$
 $= 3.23 \%$

Sample calculation for moisture change :

Cycle No : B $W = 2038$ gr
Sample : A $w\% = 14.0 \%$
Original oven dry wt = $\frac{2038 \times 100}{100 + 14.0} = 1786$
Moisture content = $\left(\frac{2145}{1786} - 1 \right) \times 100$
(Cycle 1) $= 20.2 \%$
 $\therefore$ Moisture change = $20.2 - 14.0 = 6.2 \%$

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FREEZE-THAW TEST RESULTS

VOLUME AND MOISTURE CHANGE

12 %

FREEZE-THAW CYCLES	UNIT LENGTH (VOLUME) CHANGE (CM/CM)				MOISTURE CHANGE	
	SAMPLE A		SAMPLE B		SAMPLE A (%)	SAMPLE B (%)
	FREEZE	THAW	FREEZE	THAW		
1	.0034	.0060	.0017	.0051	3.6	2.6
2	.0060	.0094	.0034	.0060	4.5	3.2
3	.0077	.0136	.0060	.0085	5.7	3.6
4	.0111	.0102	.0094	.0119	6.5	3.7
5	.0119	.0170	.0111	.0179	5.8	4.2
6	.0111	.0145	.0111	.0180	5.6	5.2
7	.0144	.0184	.0153	.0204	7.5	6.0
8	.0161	.0179	.0170	.0230	7.8	7.2
9	.0187	.0238	.0204	.0280	7.7	7.3
10	.0213	.0255	.0213	.0272	8.6	7.6
11	.0238	.0280	.0230	.0264	8.8	8.2
12	.0246	.0272	.0221	.0280	8.2	8.0

Max. Volume (Length) change : 2.8 %

Max. Moisture change : 8.8 %

Sample calculation for volume (length) change :

Cycle No : 9

Sample : B

Original length of sample $l_0 = 11.75$ cm

length of sample at 9th cycle $l_9 = 12.08$ cm

$$\begin{aligned} \therefore \text{Volume (length) change} &= \frac{(l_9 - l_0) 100}{l_0} \\ &= \frac{(12.08 - 11.75) 100}{11.75} \\ &= 2.80 \% \end{aligned}$$

Sample calculation for moisture change :

Cycle No : 11

Sample : A

$W = 2036$ gr

$w \% = 14.3 \%$

Original oven dry wt = $\frac{2036 \times 100}{100 + 14.3} = 1776$

Moisture content = $\frac{(2189 - 1776)}{1776} \times 100$
(Cycle 11)
 $= 23.1 \%$

$\therefore$ Moisture change = $23.1 - 14.3 = 8.8 \%$

FREEZE - THAW - TEST RESULTS

VOLUME AND MOISTURE CHANGE

15%

FREEZE - THAW CYCLES	UNIT LENGTH (VOLUME) CHANGE (Δl/Δt)				MOISTURE CHANGE	
	SAMPLE A		SAMPLE B		SAMPLE A (%)	SAMPLE B (%)
	FREEZE	THAW	FREEZE	THAW		
1	.0017	.0043	.0008	.0034	2.8	3.8
2	.0043	.0077	.0025	.0042	4.6	4.1
3	.0034	.0093	.0034	.0068	4.6	4.8
4	.0067	.0085	.0034	.0077	5.1	4.9
5	.0077	.0110	.0042	.0068	5.9	5.3
6	.0085	.0102	.0042	.0077	6.2	5.8
7	.0077	.0119	.0068	.0093	6.8	7.0
8	.0093	.0145	.0060	.0110	6.3	6.9
9	.0119	.0170	.0093	.0127	6.9	6.9
10	.0136	.0179	.0102	.0119	6.9	7.1
11	.0123	.0170	.0127	.0144	7.1	6.9
12	.0153	.0187	.0145	.0170	7.0	6.9

Max. Volume (length) change : 1.87 %

Max. Moisture change : 7.1 %

Sample calculation for volume (length) change :

Cycle No : 12
 Sample : A
 Original length of sample $l_0 = 11.76$ cm
 Length of sample at 12th cycle $l_2 = 11.98$

$$\therefore \text{Volume (length) change} = \frac{(l_2 - l_0)100}{l_0}$$

$$= \frac{(11.98 - 11.76)100}{11.76}$$

$$= 1.87 \%$$

Sample calculation for moisture change :

Cycle No : 11
 Sample : A
 $W = 2042$ gr
 $w = 14.91 \%$
 Original oven dry wt = $\frac{2042 \times 100}{100 + 14.91} = 1781$
 Moisture content = $\left(\frac{2171}{1781} - 1 \right) \times 100$
 (cycle 11)
 $= 22.0 \%$
 $\therefore \text{Moisture change} = 22.0 - 14.9 = 7.1 \%$

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SOIL - CEMENT LOSSES

(At optimum water content and maximum dry density)

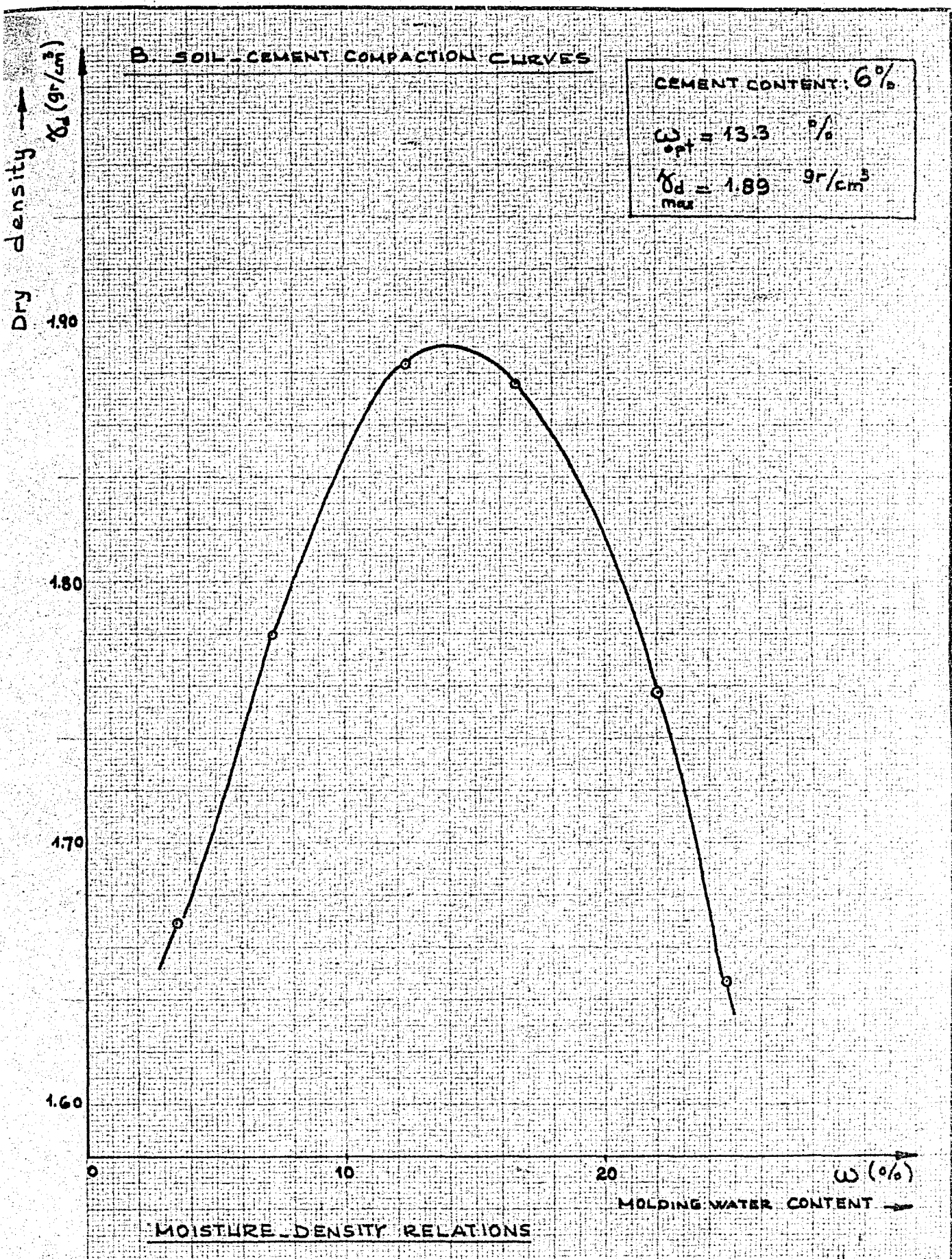
WETTING AND DRYING			FREEZING AND THAWING		
CEMENT CONTENT (%)	SOIL - CEMENT LOSS (%)		CEMENT CONTENT (%)	SOIL - CEMENT LOSS (%)	
	SAMPLE A	SAMPLE B		SAMPLE A	SAMPLE B
6	100.0 *	100.0 *	6	8.80	8.24
9	28.2	27.0	9	8.95	7.16
12	18.0	18.1	12	16.50 **	17.90 **
15	6.8	7.9	15	4.56	6.25

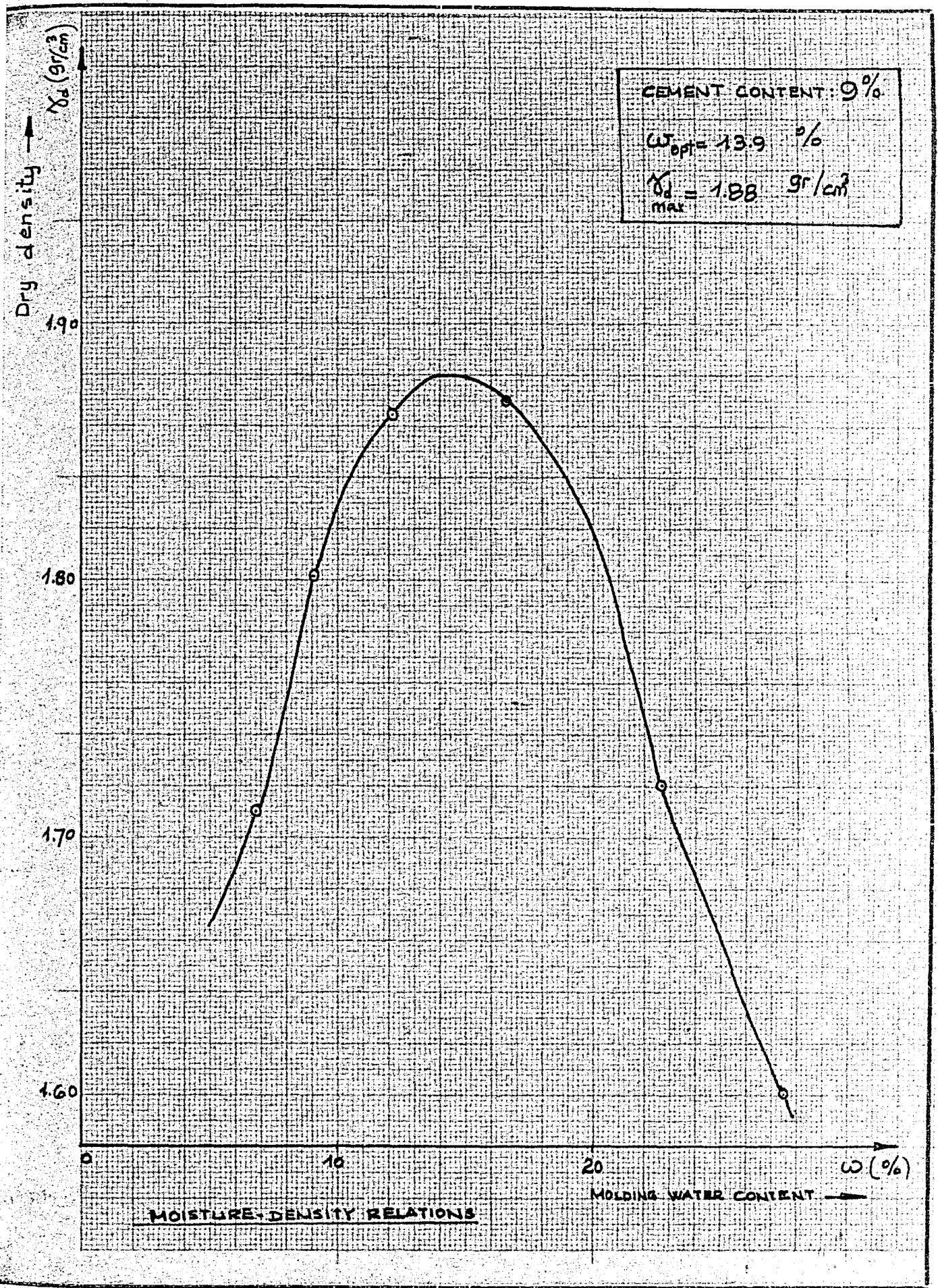
SOIL - CEMENT LOSSES

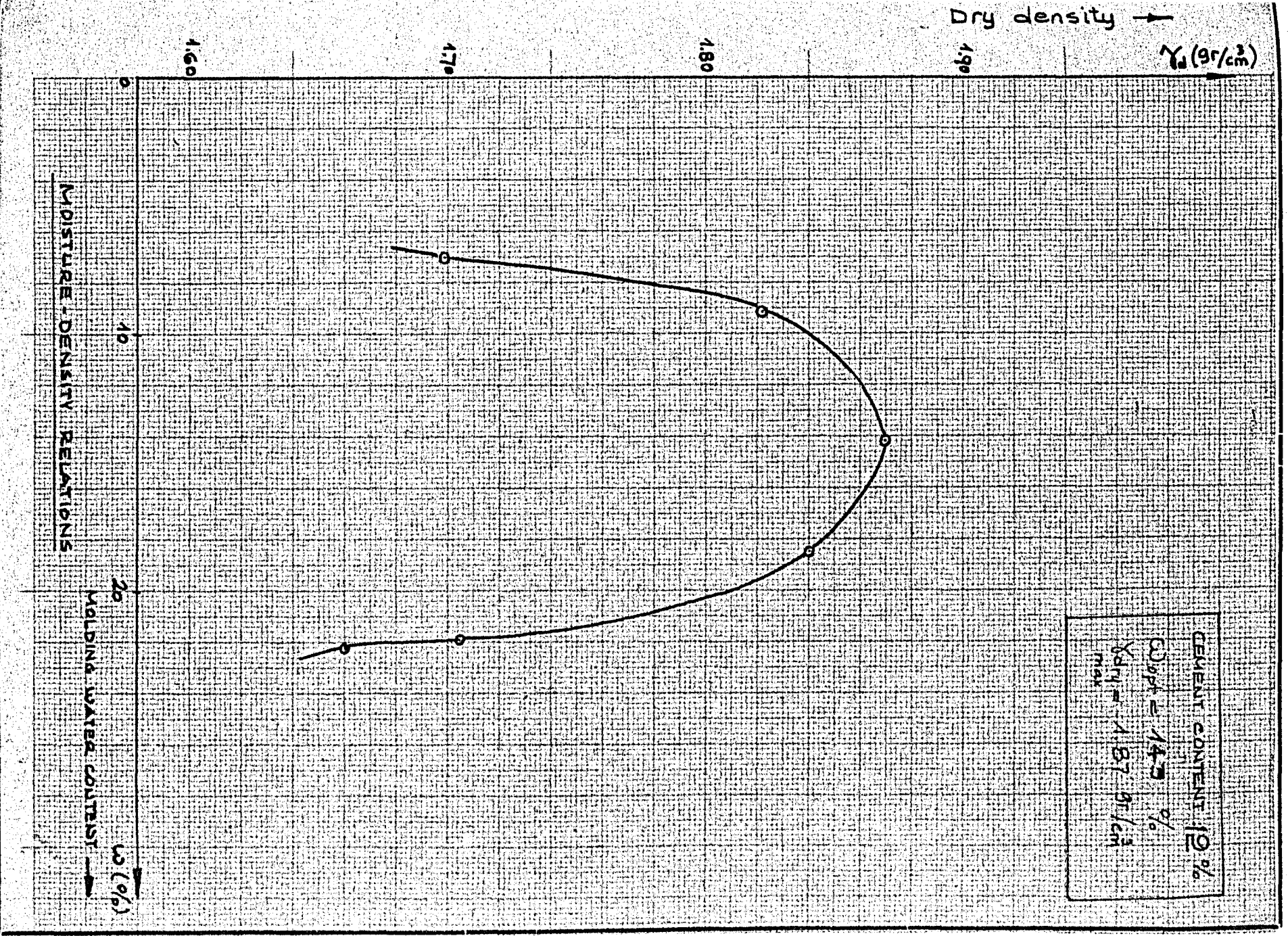
(Variation with density)

CEMENT CONTENT (%)	DRY DENSITY (g/cm^3)	WET - DRY LOSS (%)
9 ***	1.81	35.5
	1.83	31.9
	1.86	27.0
	1.87	28.2
	1.90	25.1
	1.92	22.2
12	1.81	27.9
	1.84	23.5
	1.87	18.0
	1.87	18.1
	1.89	20.3
	1.91	14.3
15	1.80	16.5
	1.82	11.8
	1.85	6.8
	1.86	7.9
	1.89	4.3
	1.88	5.7

* - these samples were disintegrated in water ** - absorbed too much water during thawing
 ** - these 6 samples were disintegrated when submerged for a period of 5-hr.



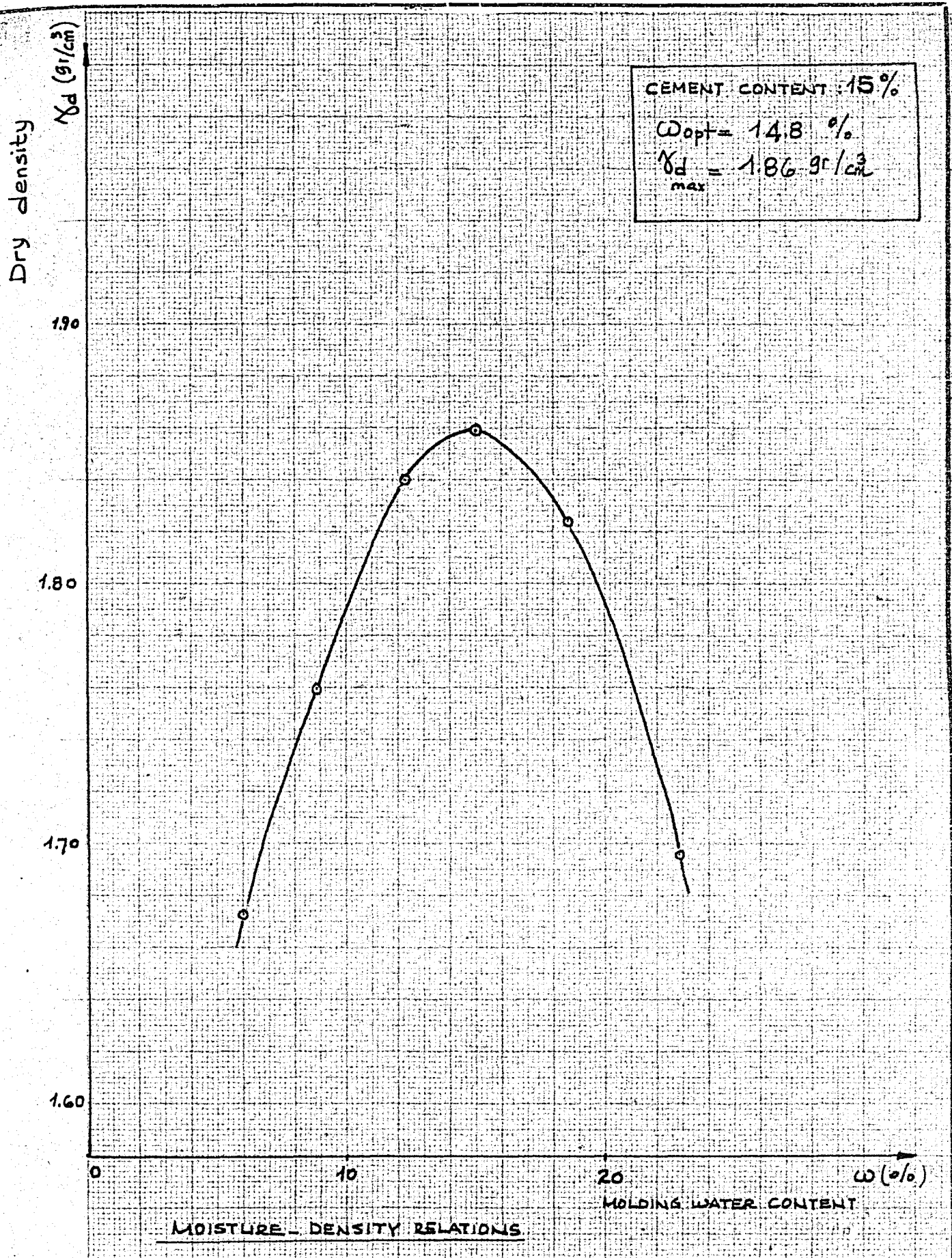




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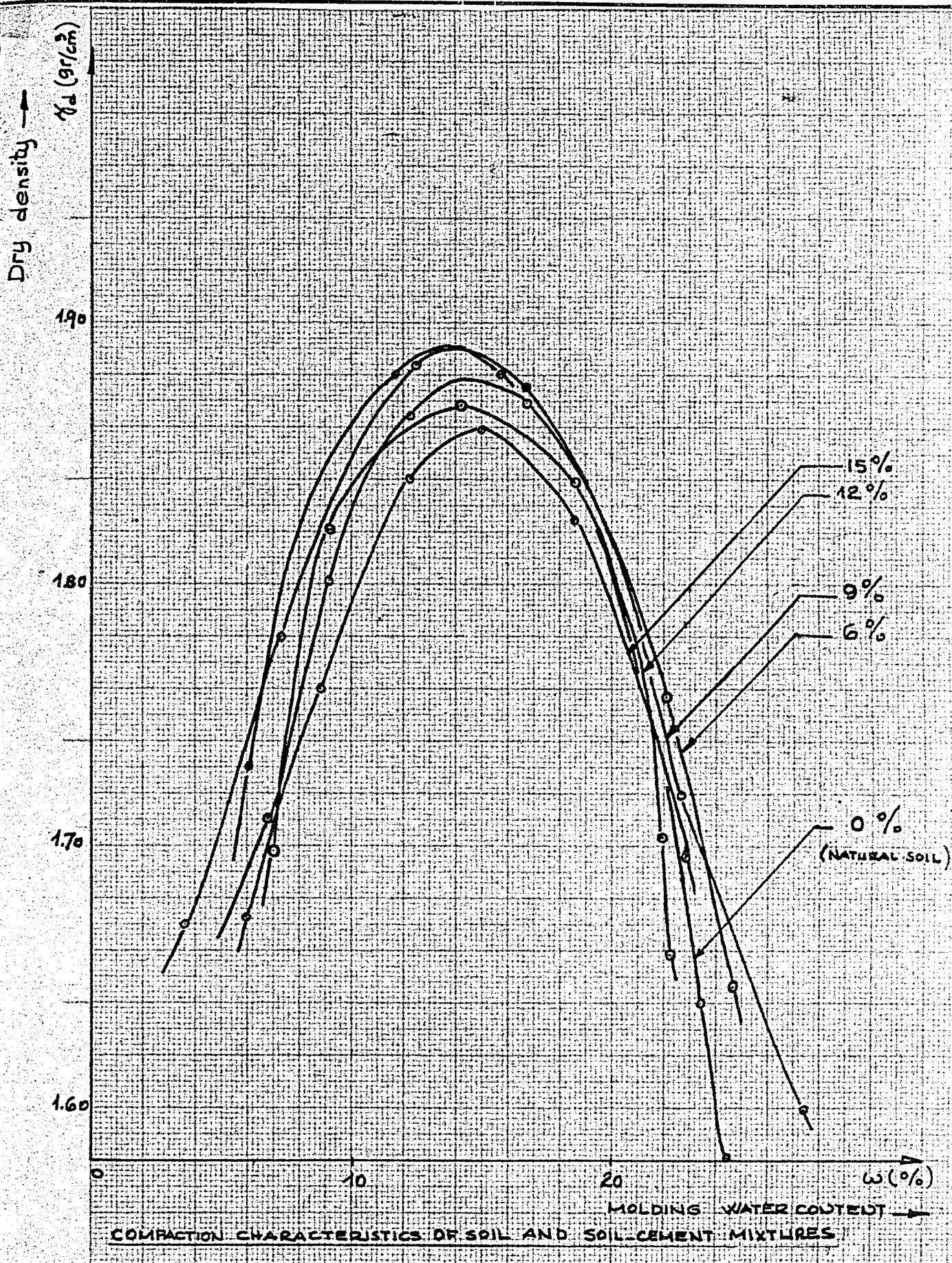
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BEBEK, ISTANBUL

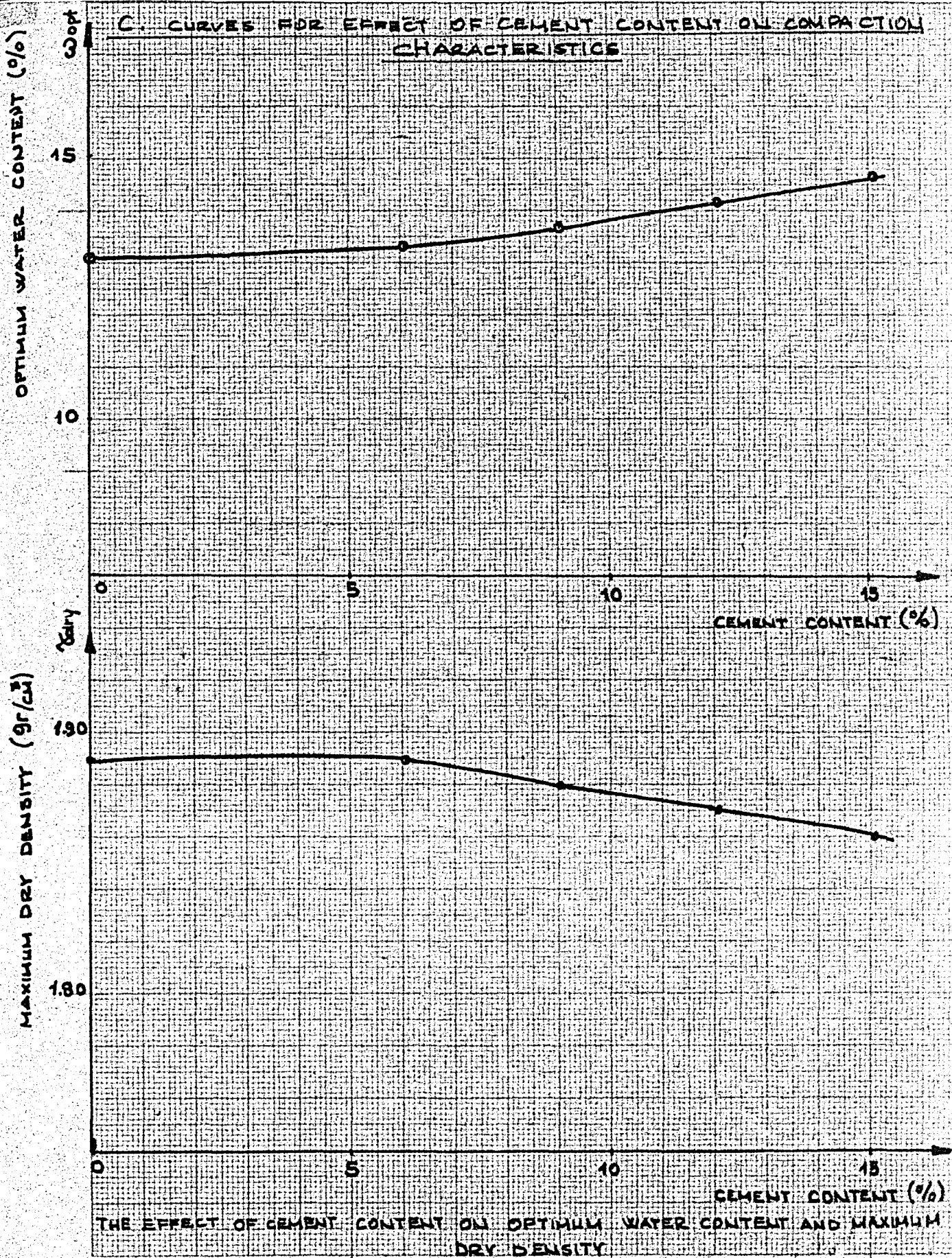
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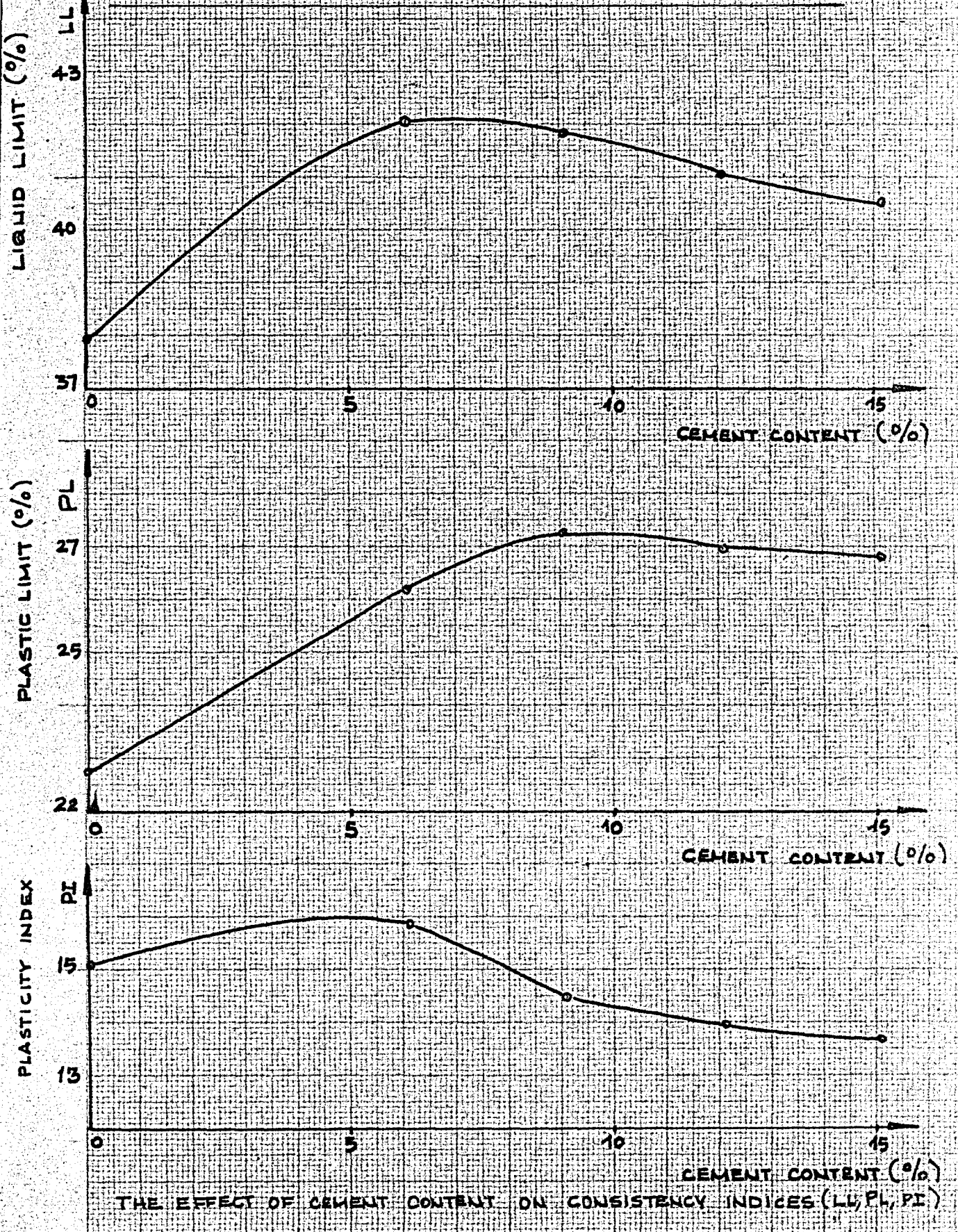


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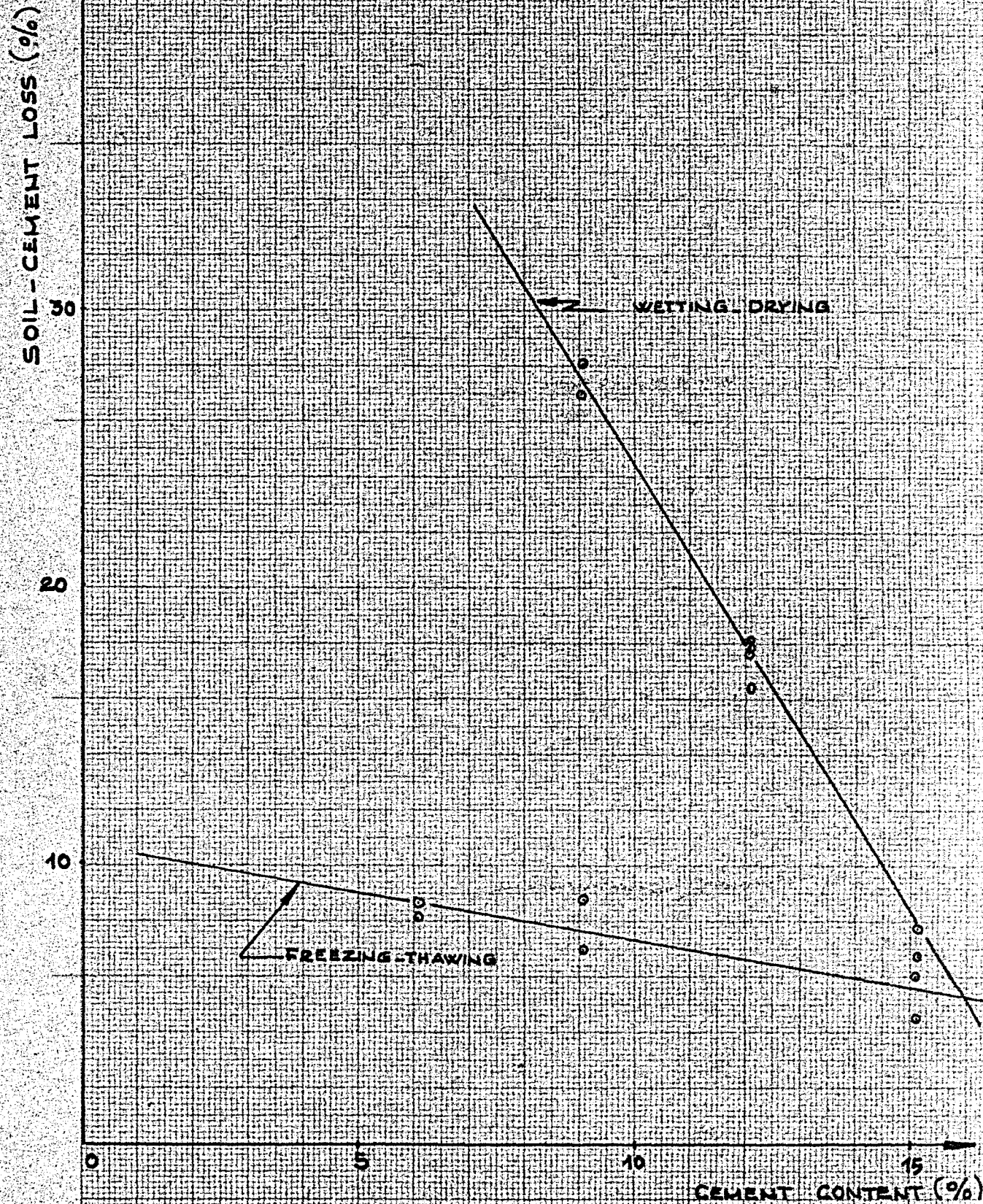
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D. CURVES FOR CONSISTENCY INDICES OF SOIL-CEMENT



E. WET-DRY AND FREEZE-THAW SOIL-CEMENT LOSS AND VOLUME CHANGE CURVES

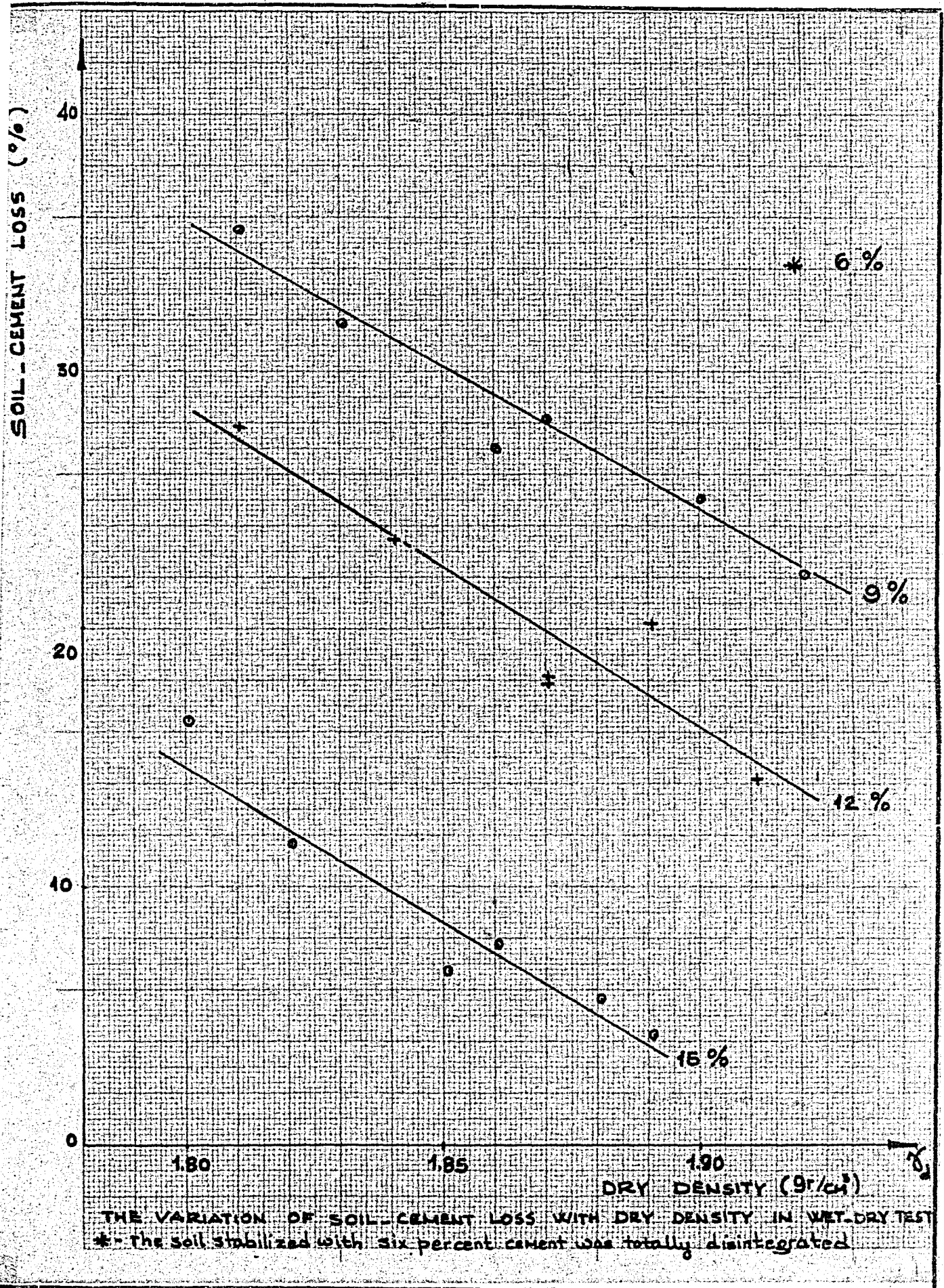


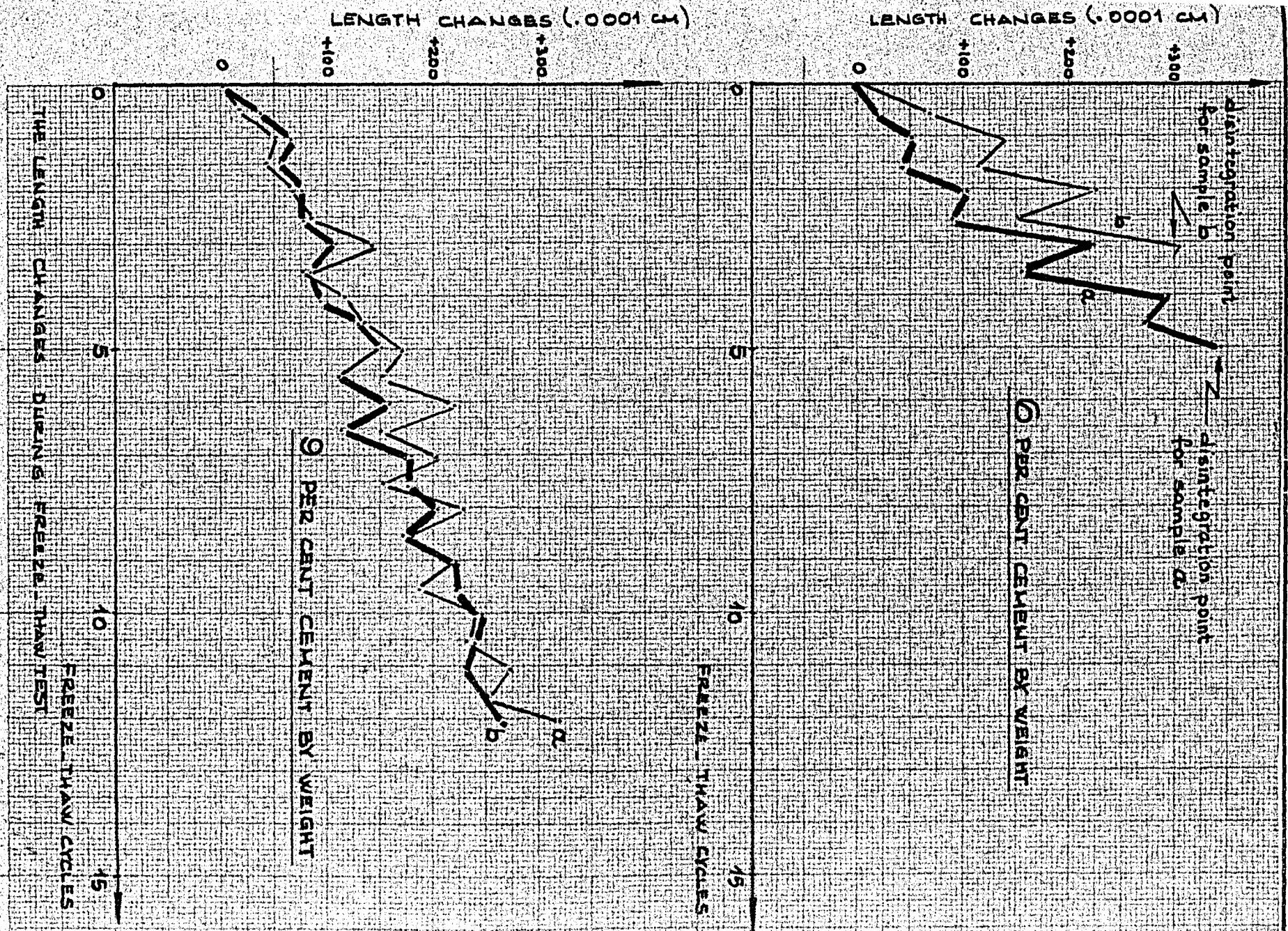
THE VARIATION OF SOIL-CEMENT LOSS WITH CEMENT CONTENT IN WET-DRY AND FREEZE-THAW TEST.

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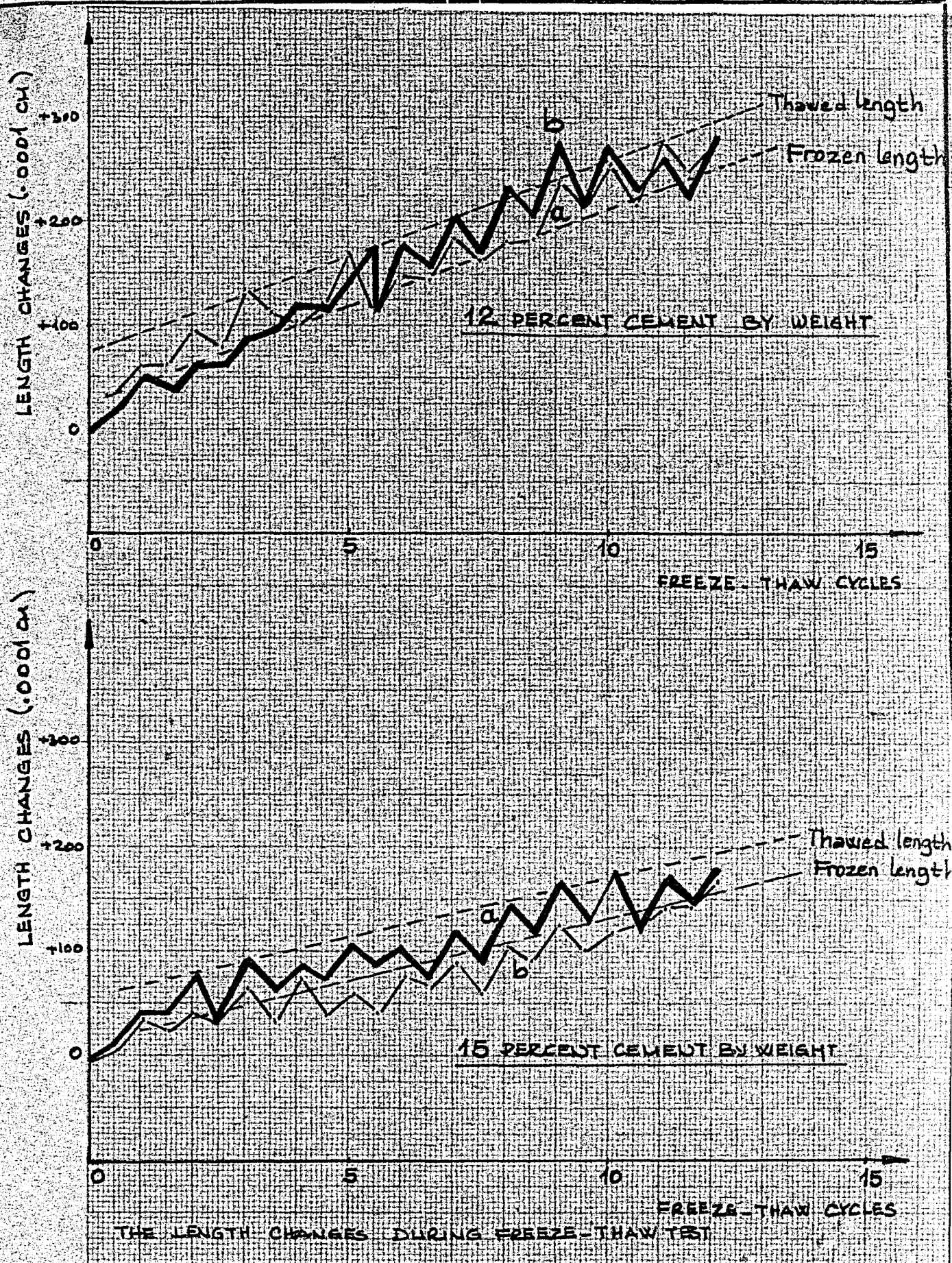




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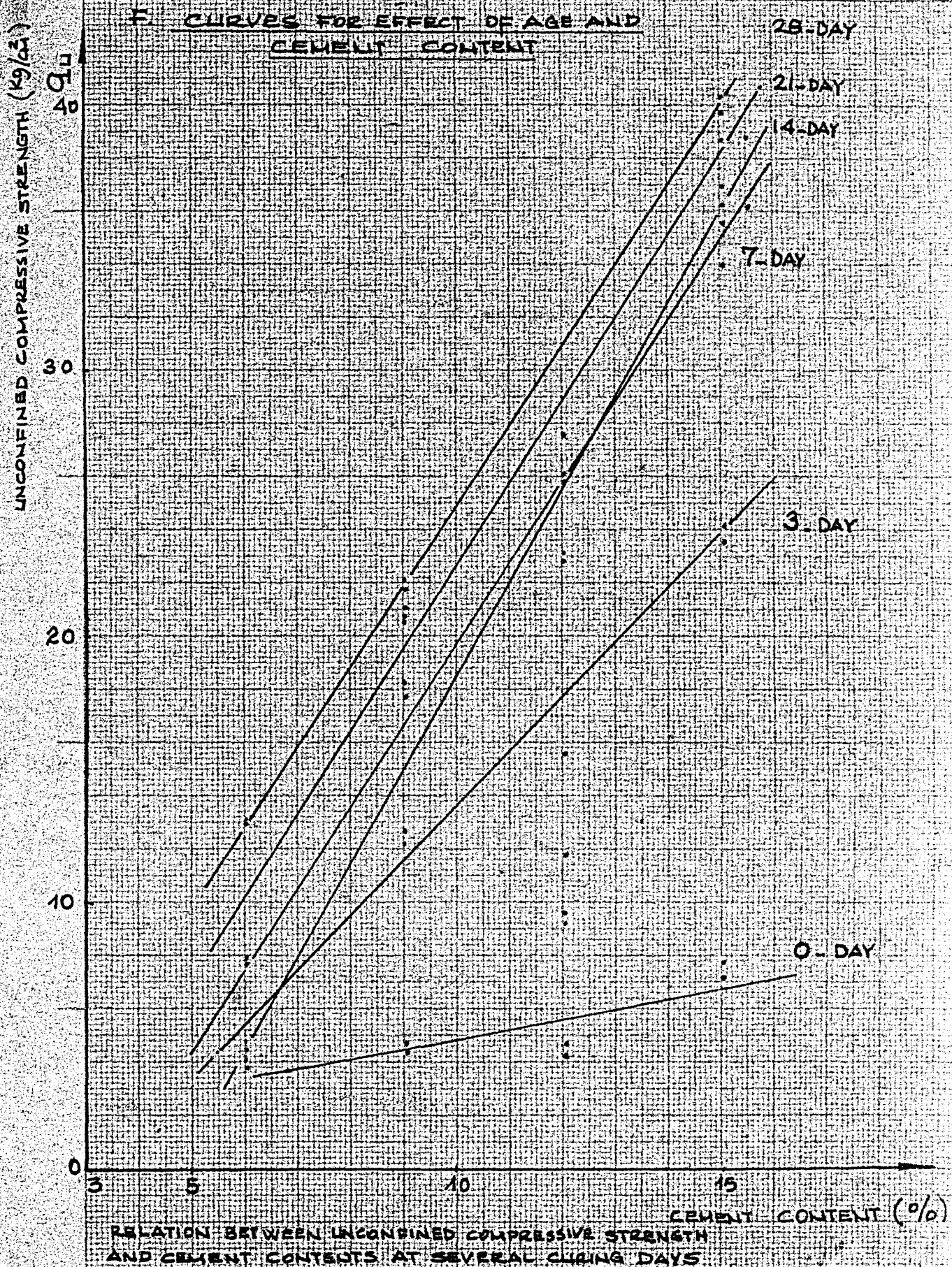
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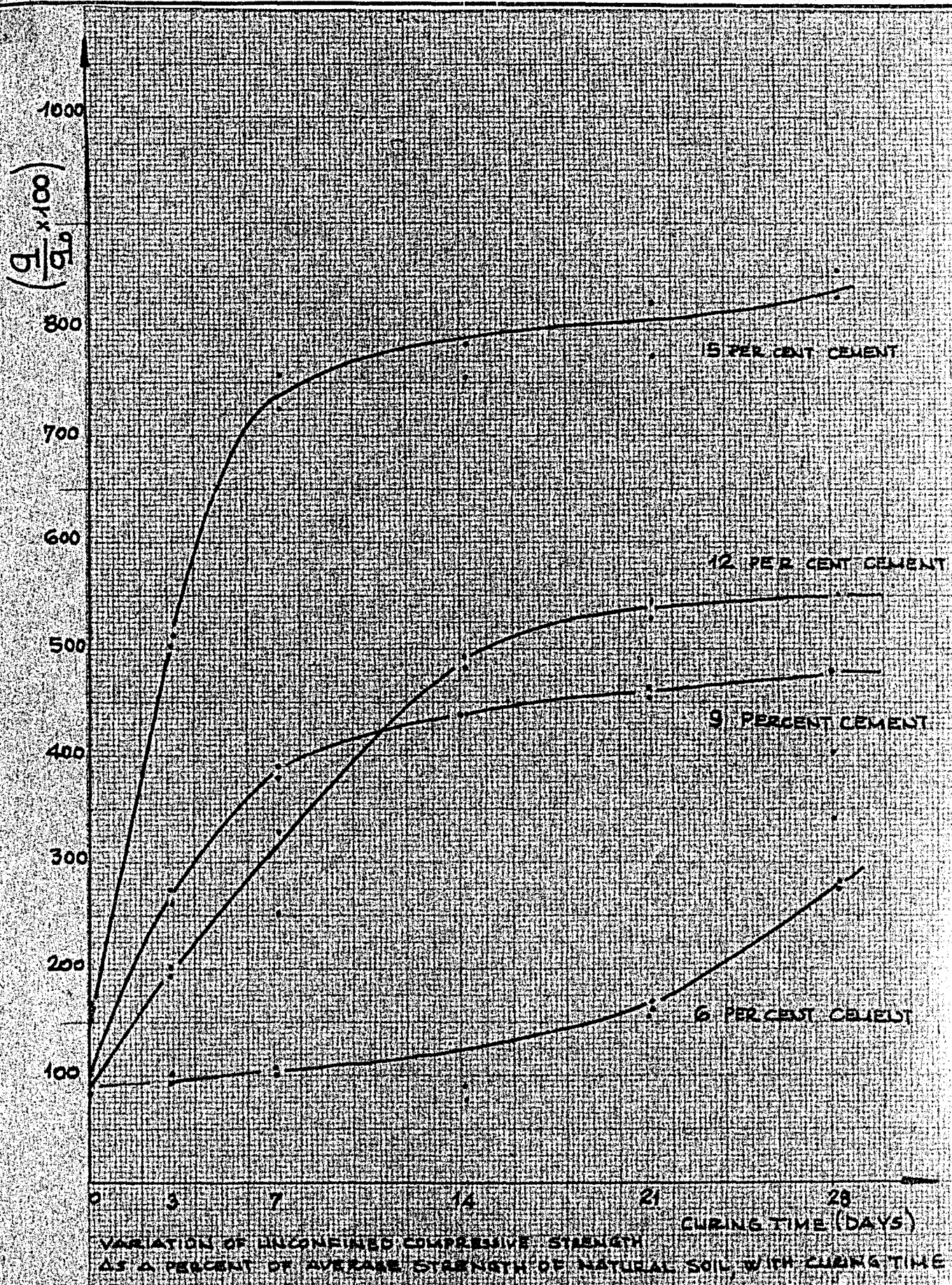
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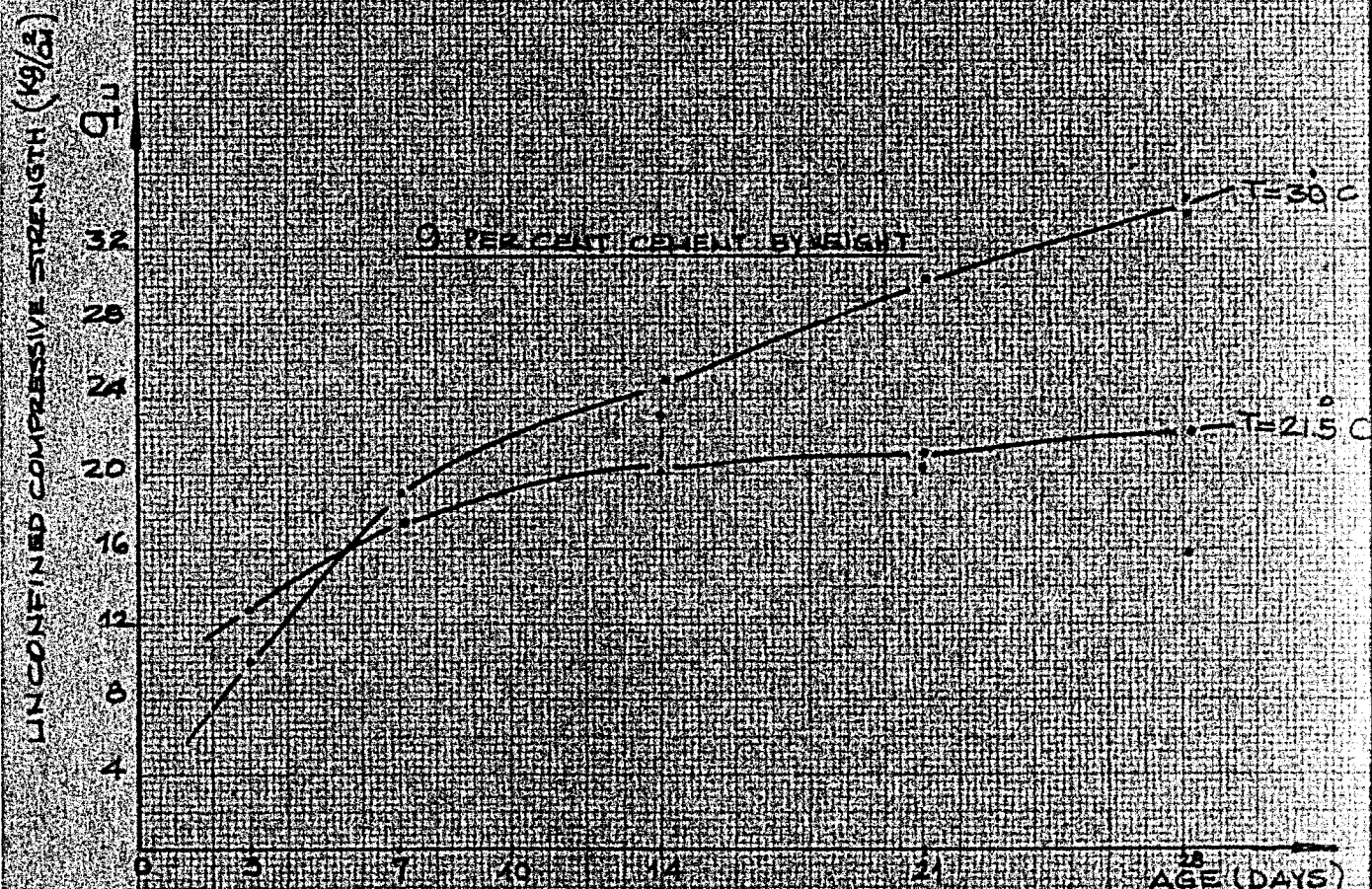
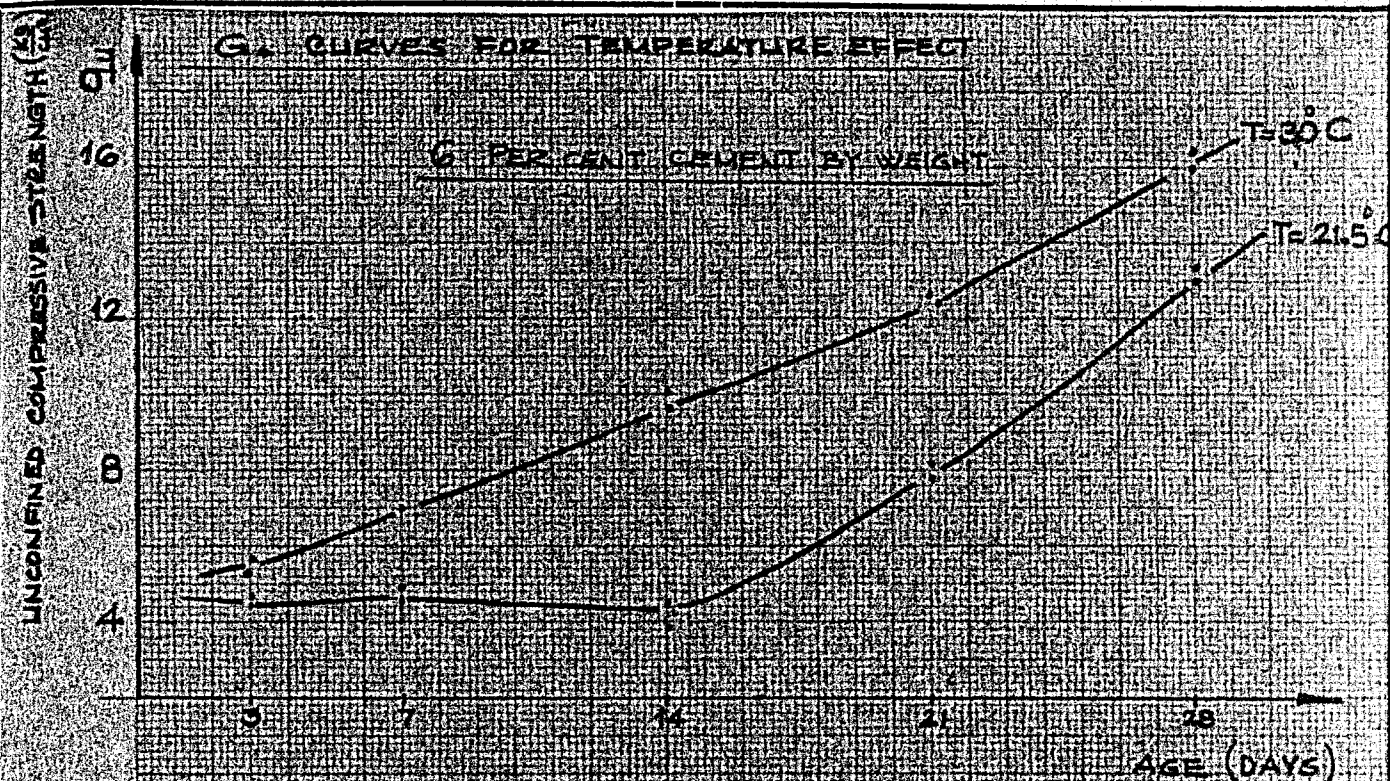


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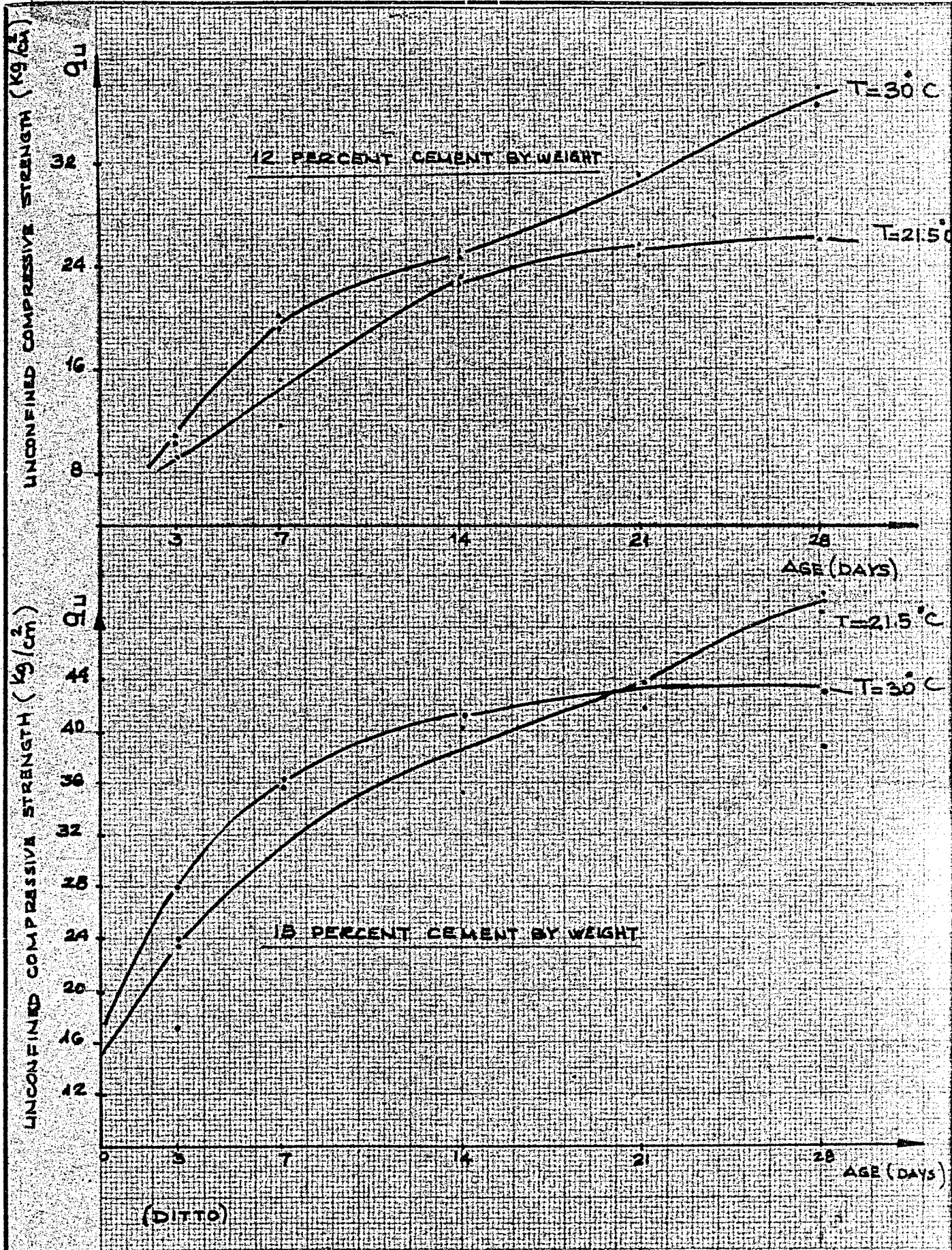


THE RELATIONSHIP BETWEEN UNCONFINED COMPRESSIVE STRENGTH AND AGE
AT TWO DIFFERENT TEMPERATURES FOR SOIL-CEMENT SAMPLES

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H. CURVES FOR EFFECT OF DENSITY

6 PERCENT CEMENT — 0-DAY

180 185 190 γ_d
DRY UNIT WEIGHT (gr/cm^3)

6 PERCENT CEMENT — 7-DAY

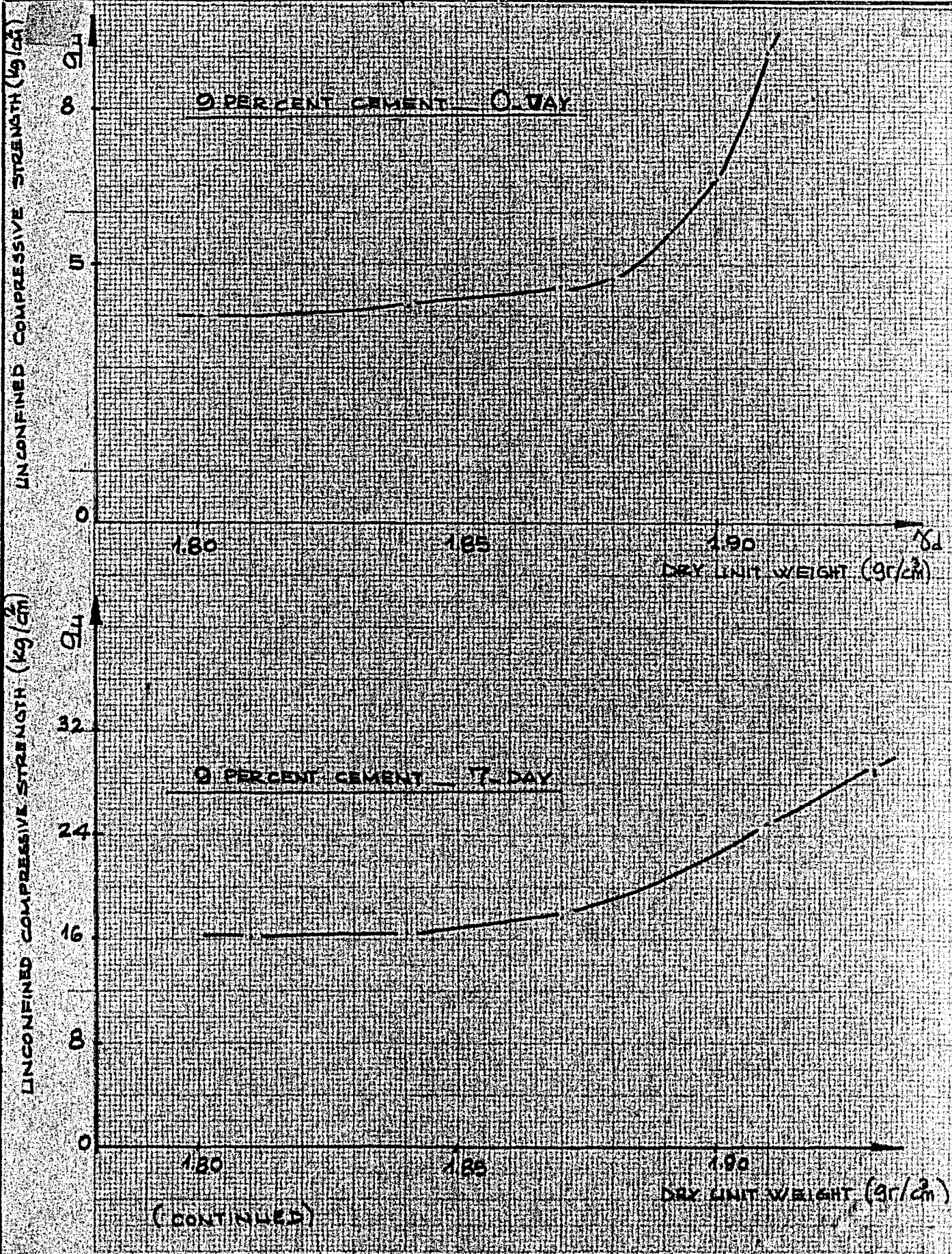
180 185 190 γ_d
DRY UNIT WEIGHT (gr/cm^3)

THE EFFECT OF DENSITY ON 0-DAY AND 7-DAY COMPRESSIVE STRENGTH

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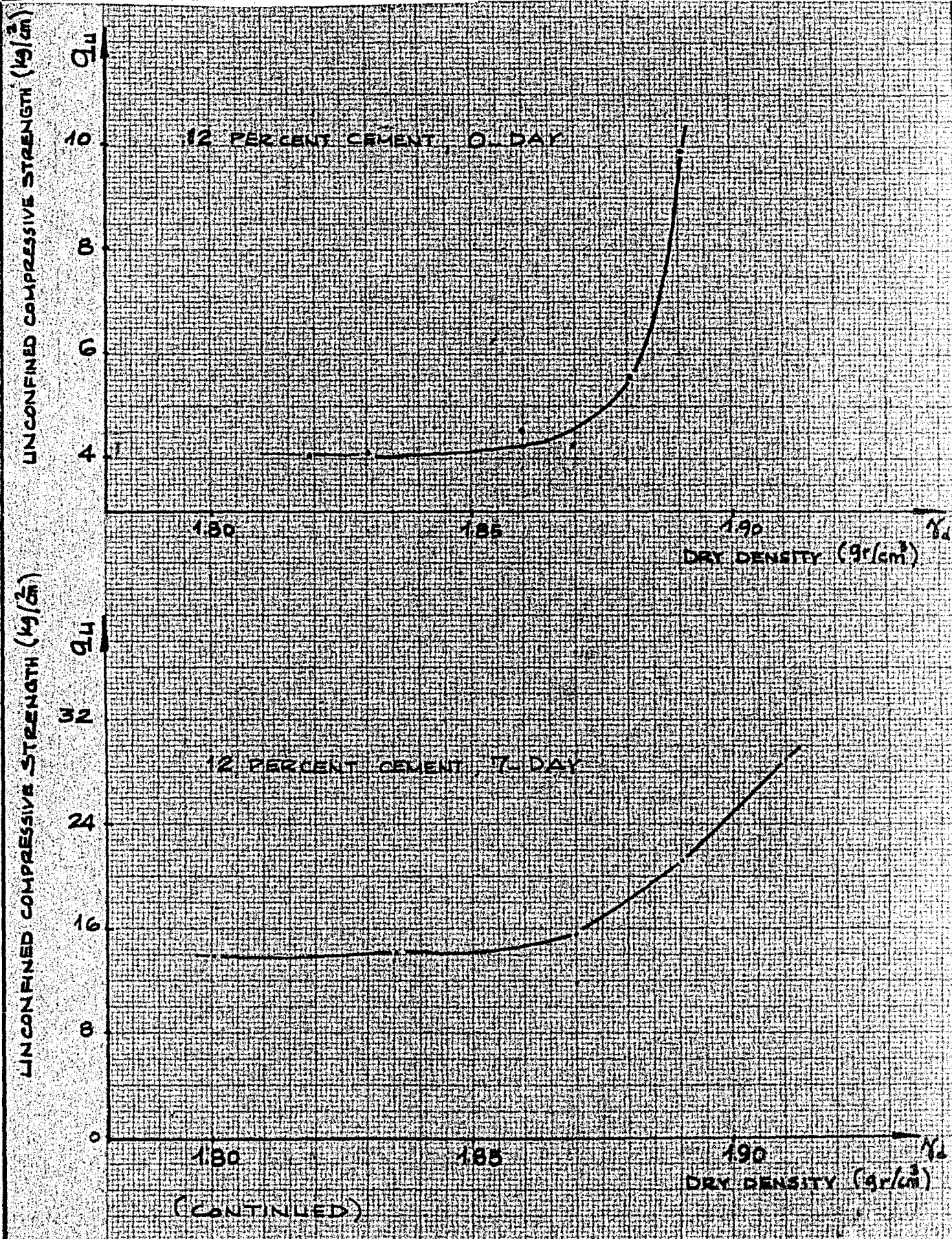
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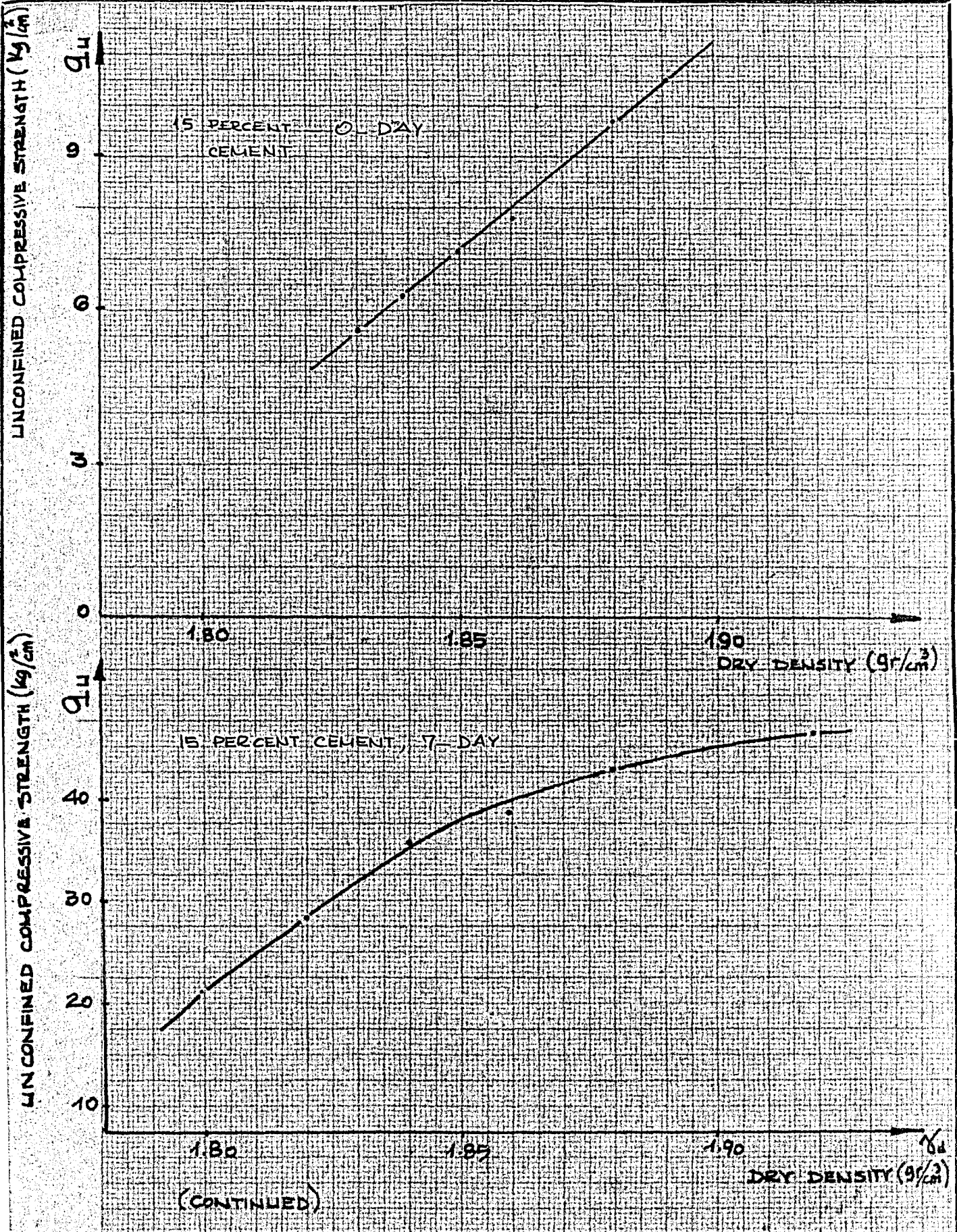
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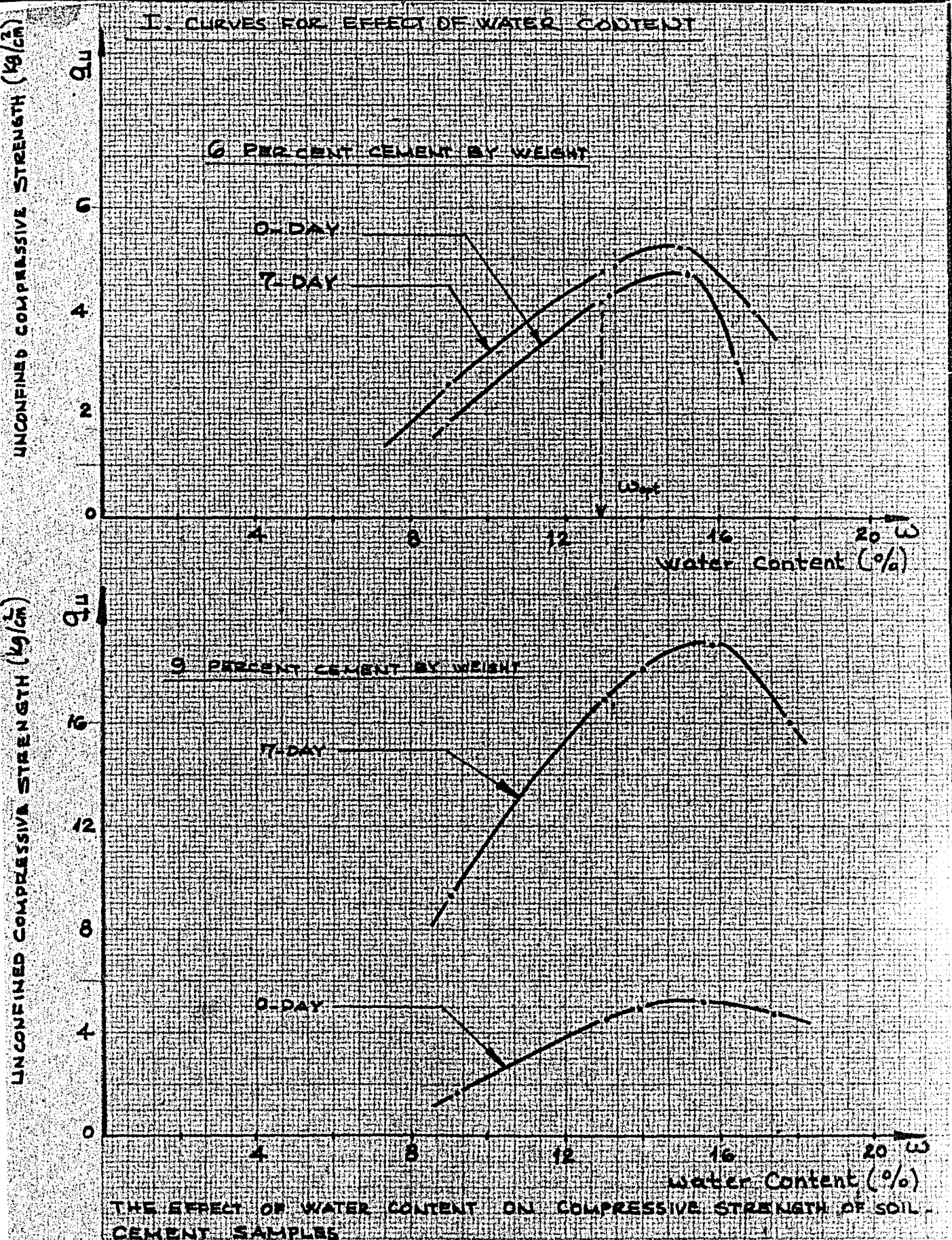
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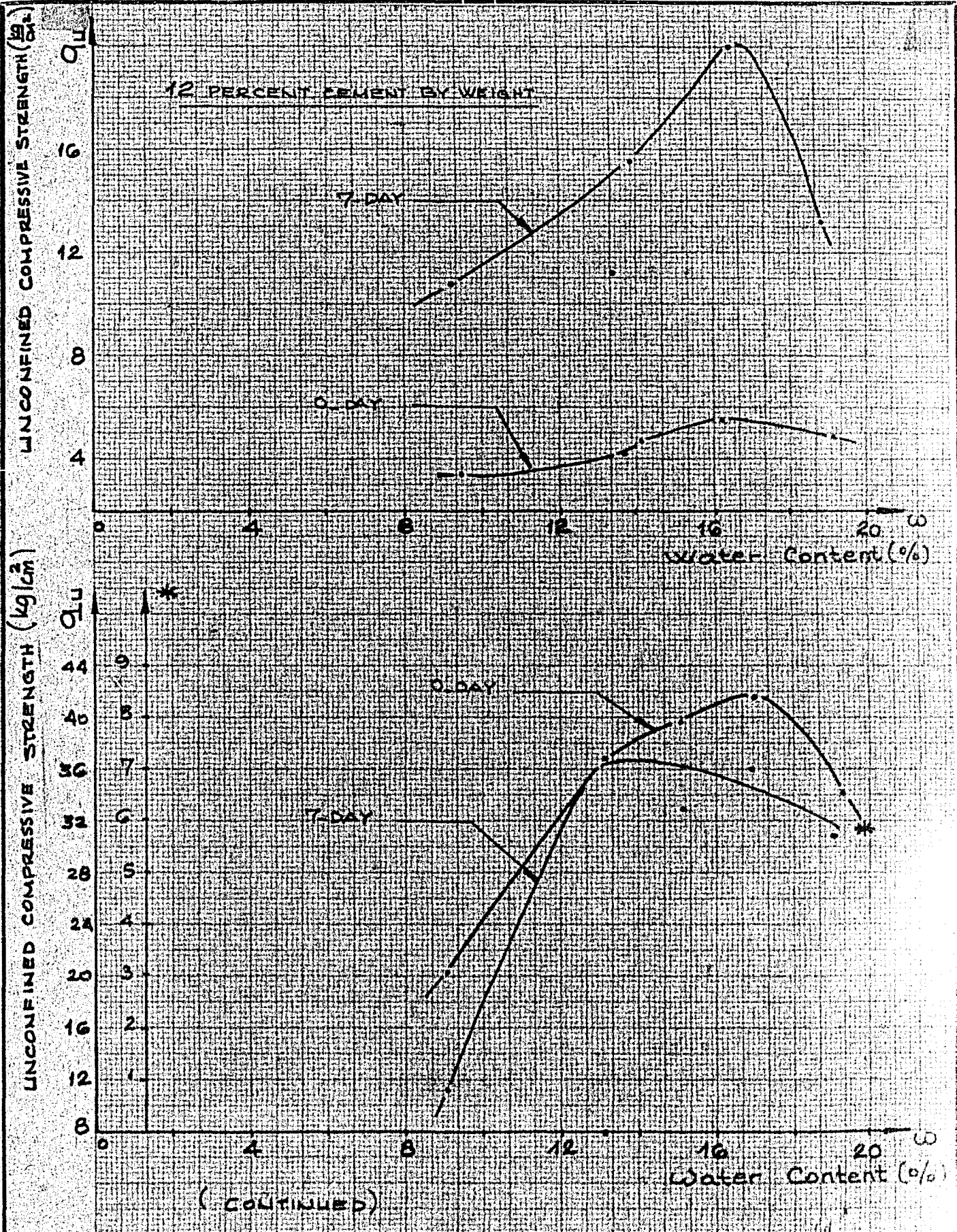
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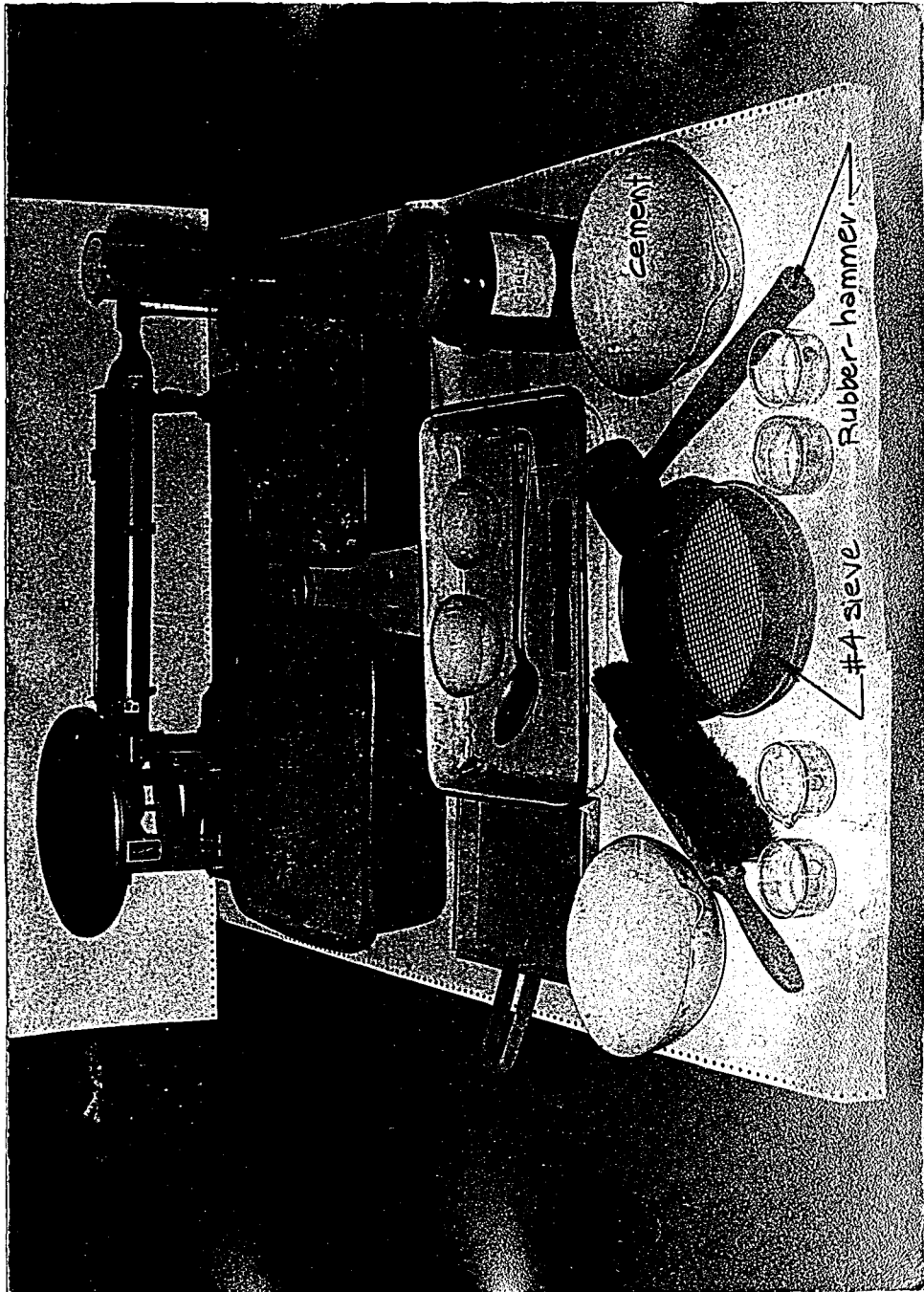


FIG. 1— SOME OF THE APPARATUS AND MATERIAL USED.

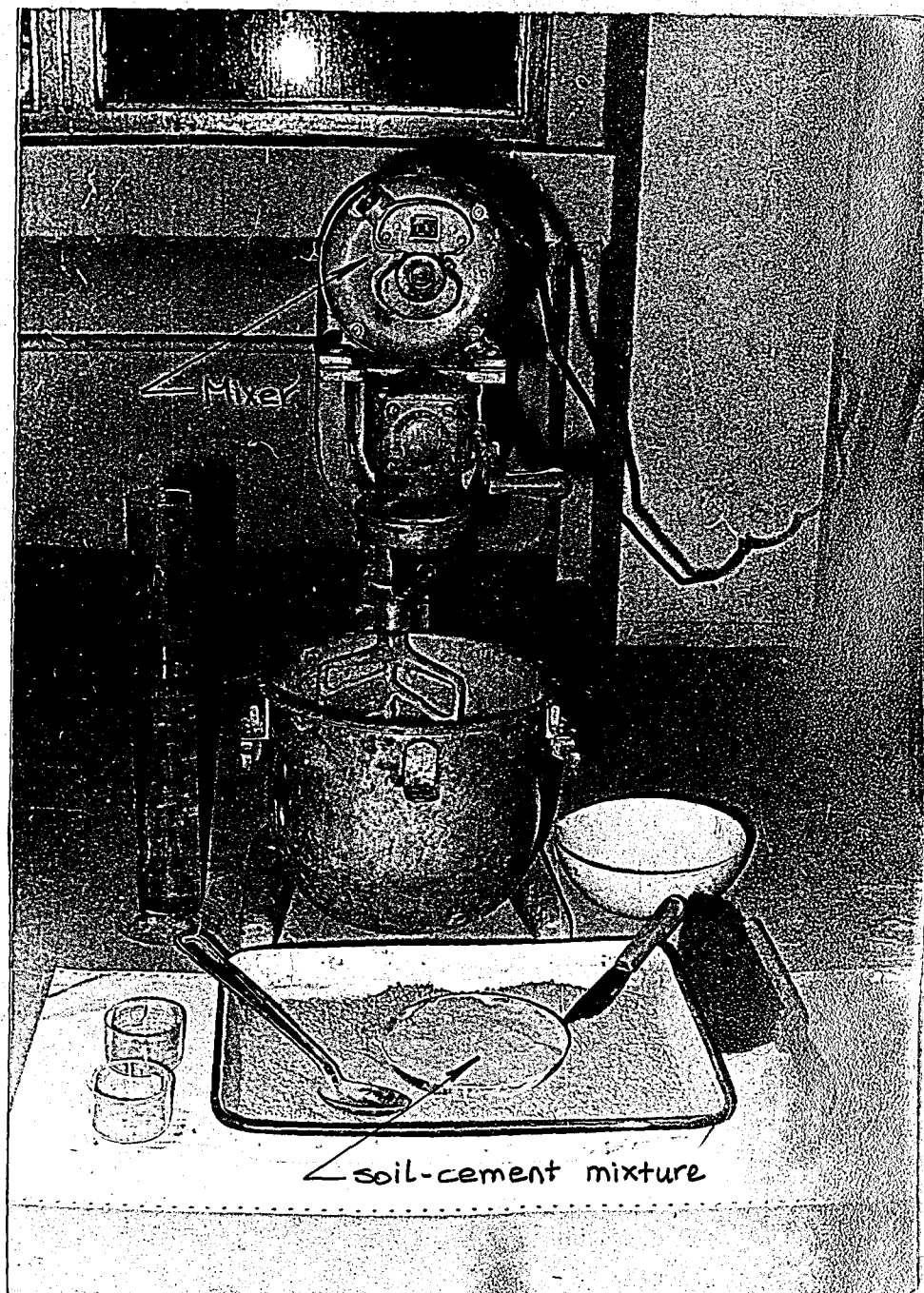


FIG. 2 — MIXING: Mixing of soil-cement

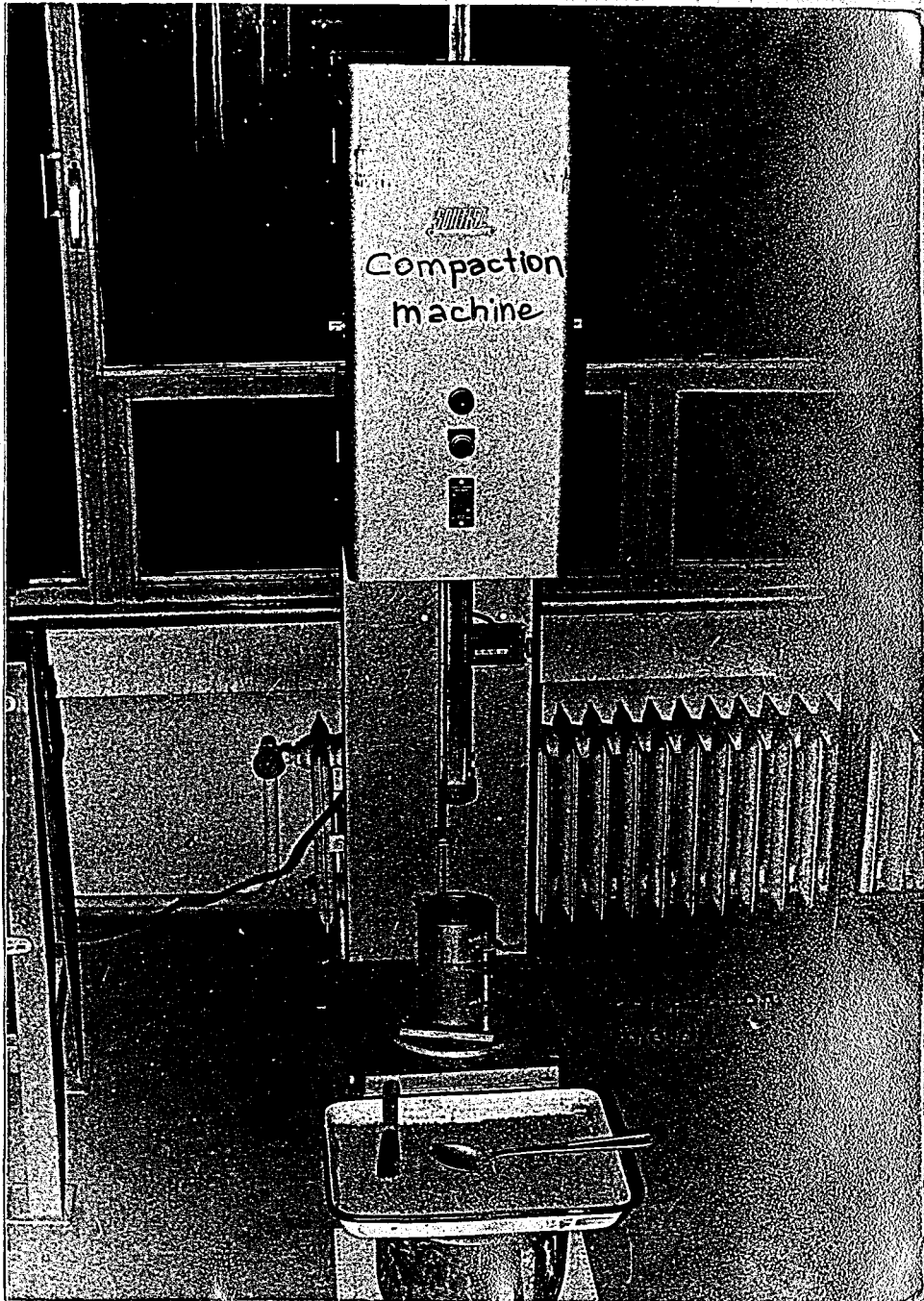


FIG.3- COMPACTION : Compaction of soil-cement mixtures.

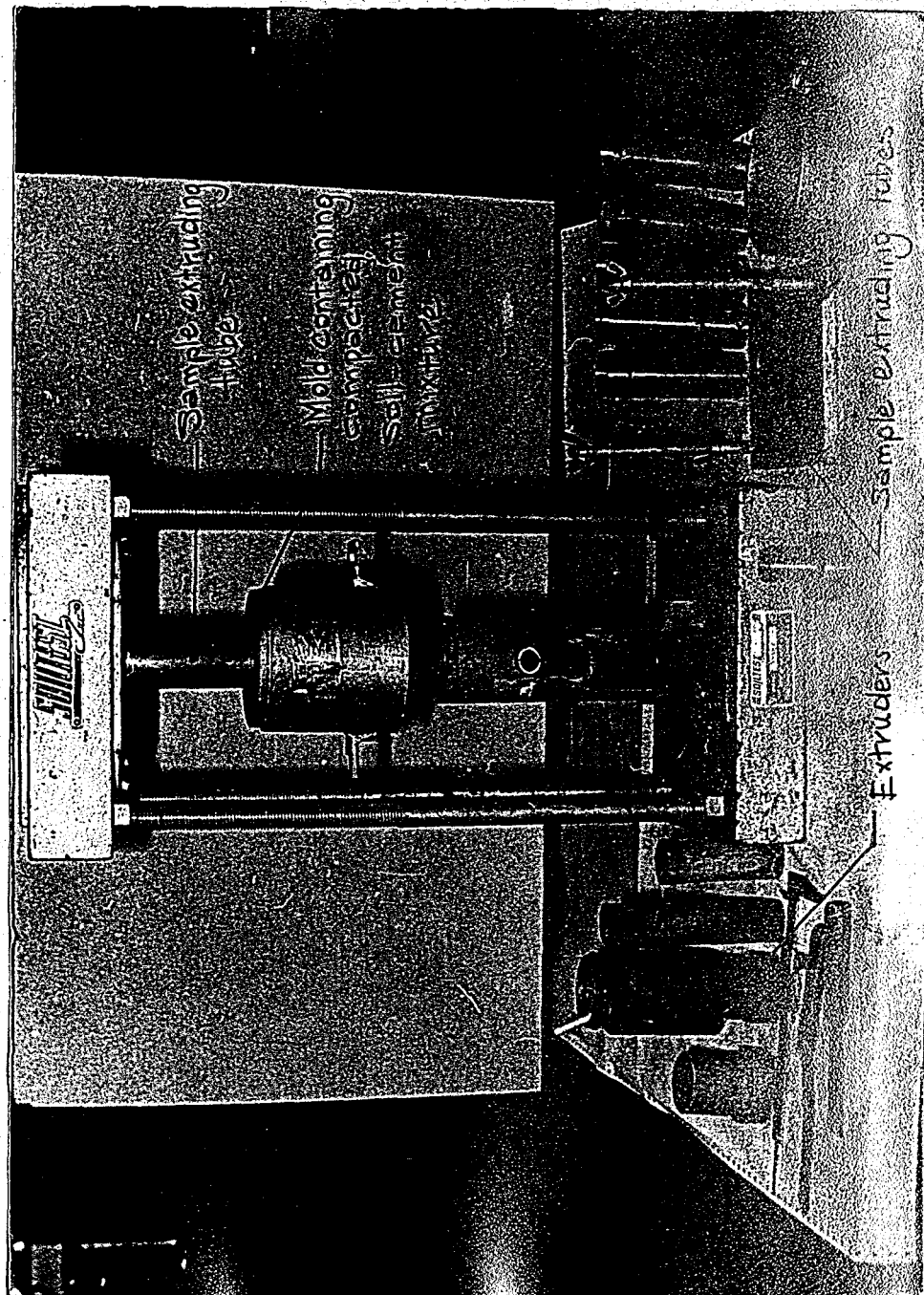


FIG. 4— EXTRUDING, Stage I: Pushing the extruding tube into the mold containing compacted soil-cement mixture.

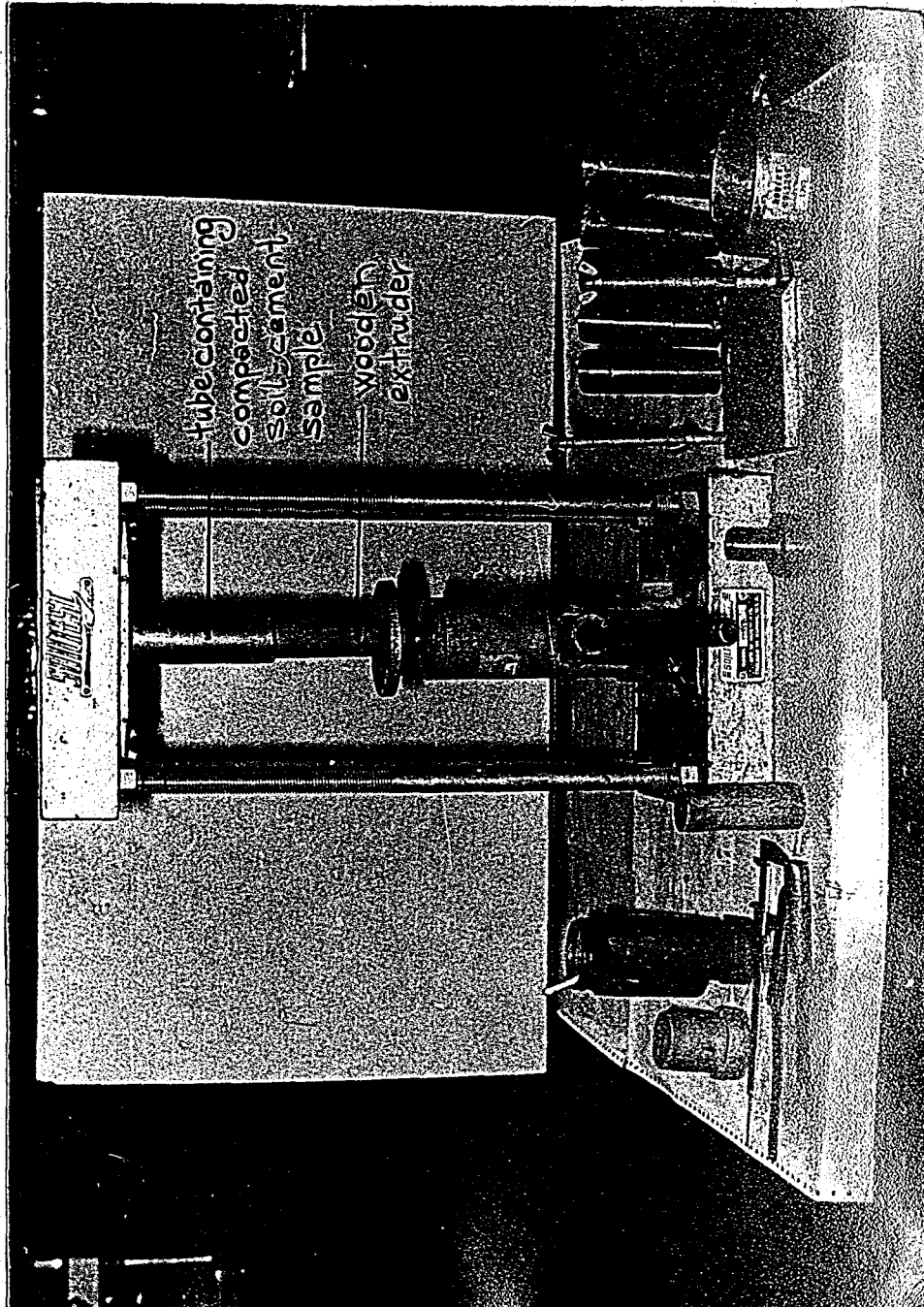


FIG. 5- EXTRUDING, Stage 2: Pushing the soil-cement sample through the extruding tube.

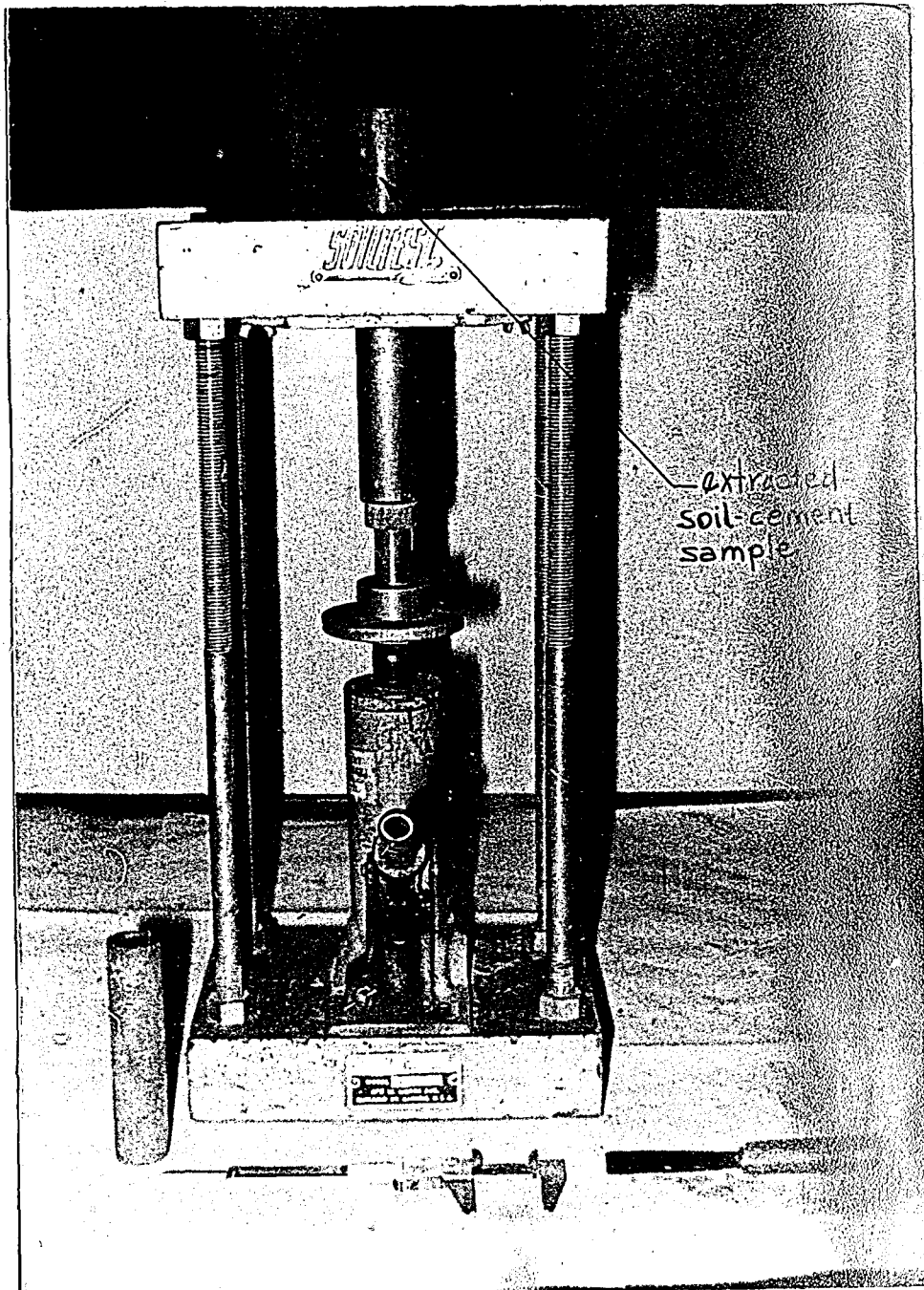


FIG. 6 - EXTRUDING, Stage 3: Obtaining the
soil-cement sample.

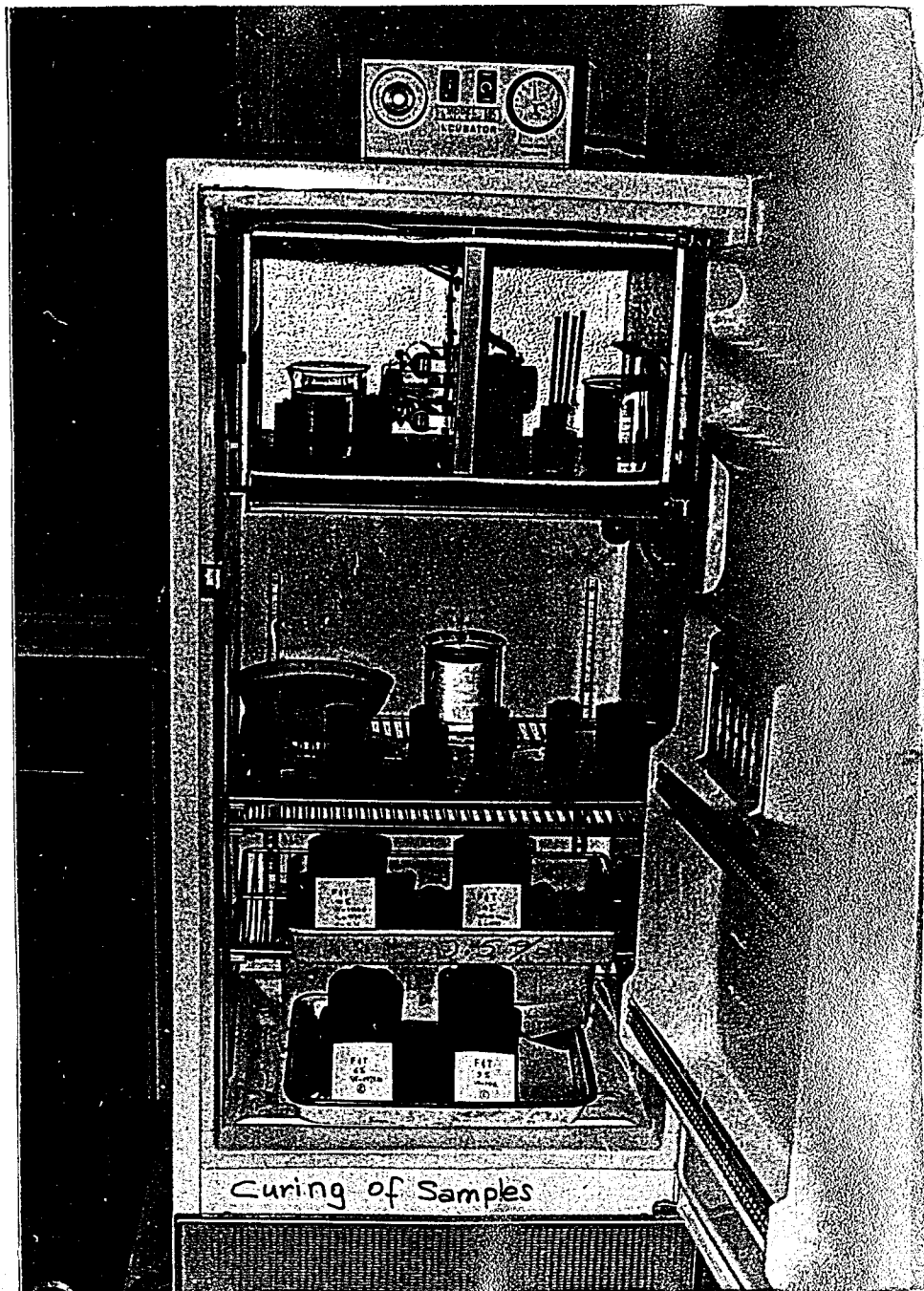


FIG.7- CURING: Curing of the wet - dry ,
freeze-thaw and unconfined samples

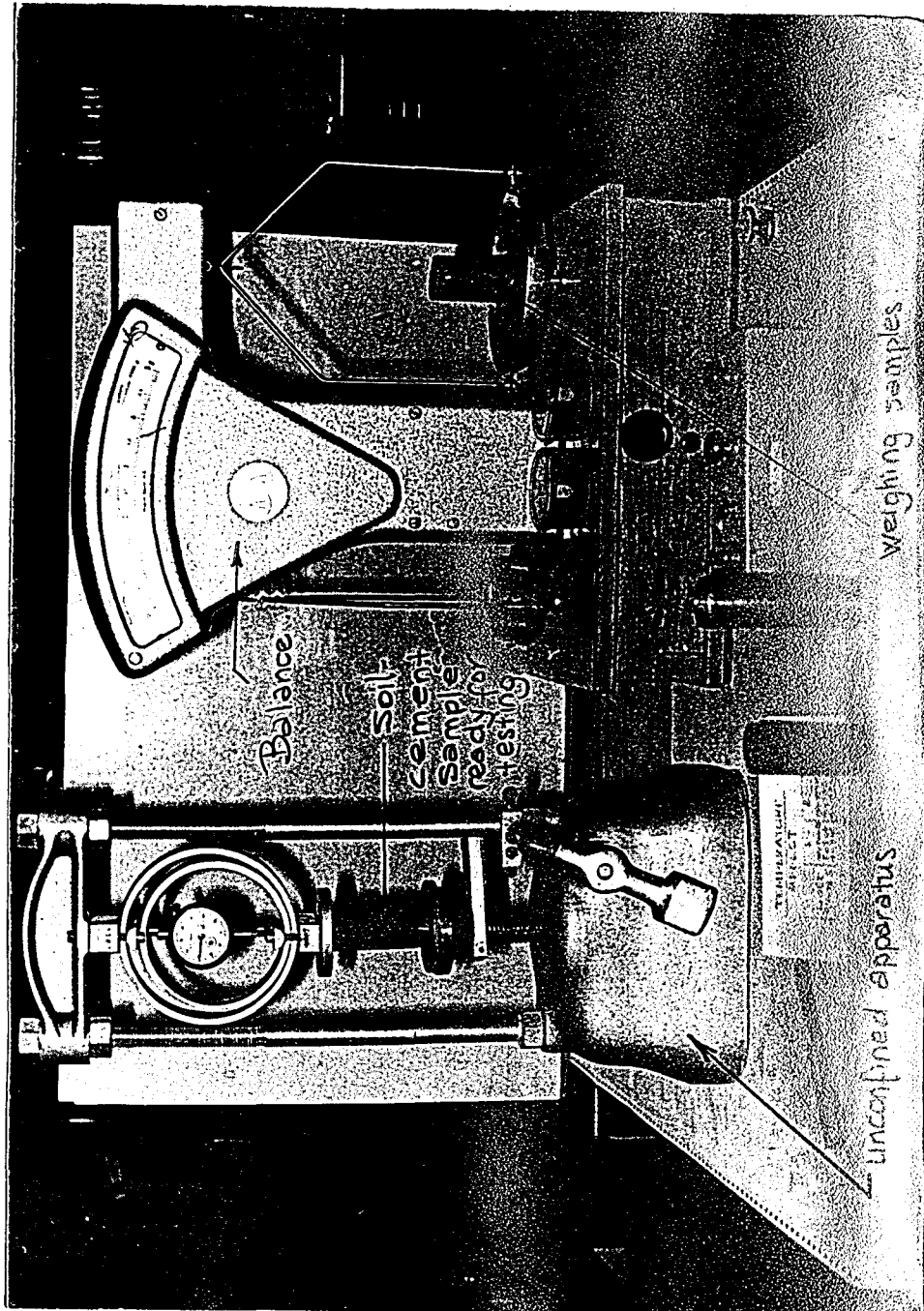


FIG. 8— WEIGHING AND TESTING : Weighing and testing of samples
for unconfined compressive strength .

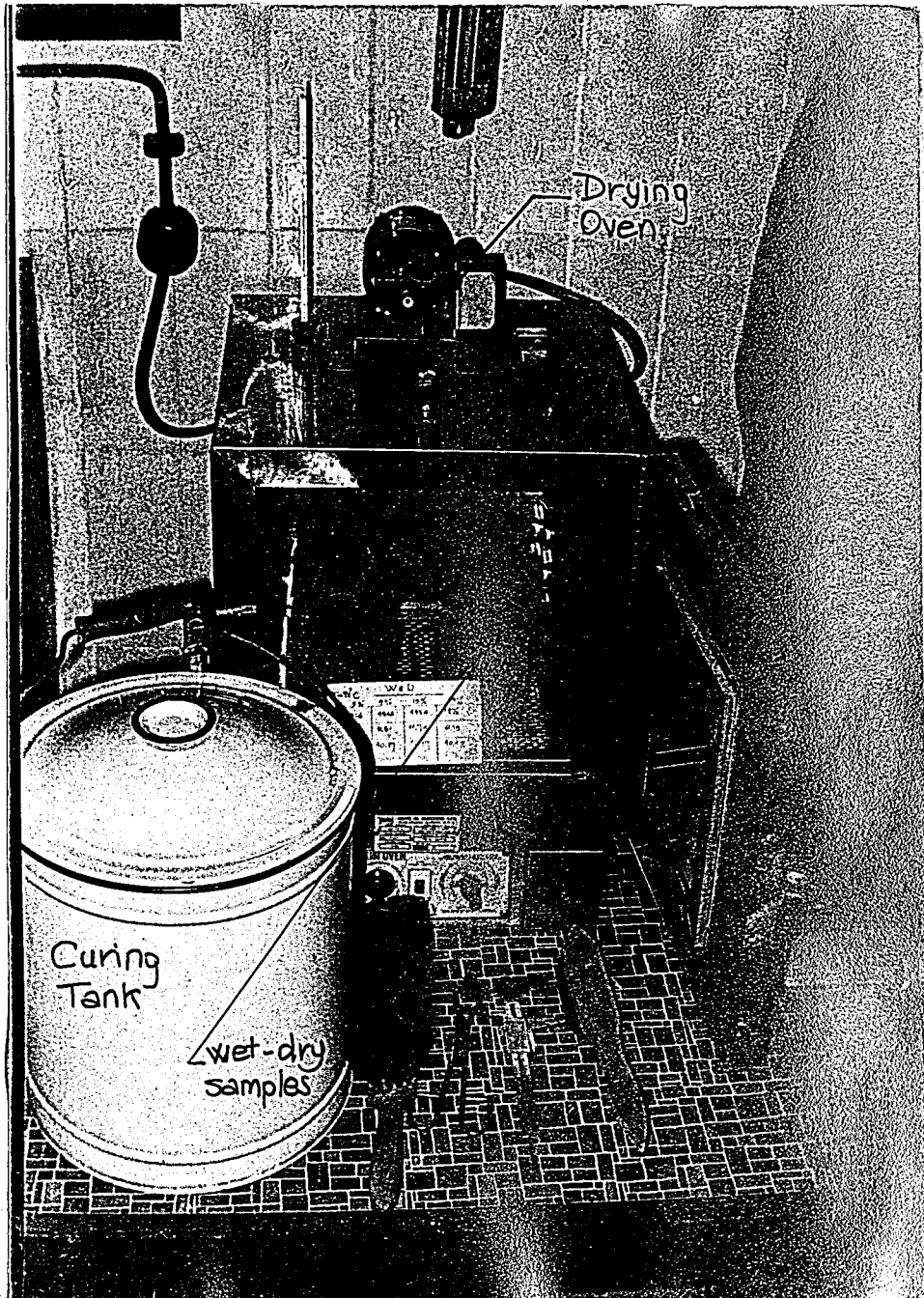


FIG. 9 — DRYING : Drying of wet-dry samples.



FIG.10— FREEZING: Freezing of samples in a
freezing-cabinet.

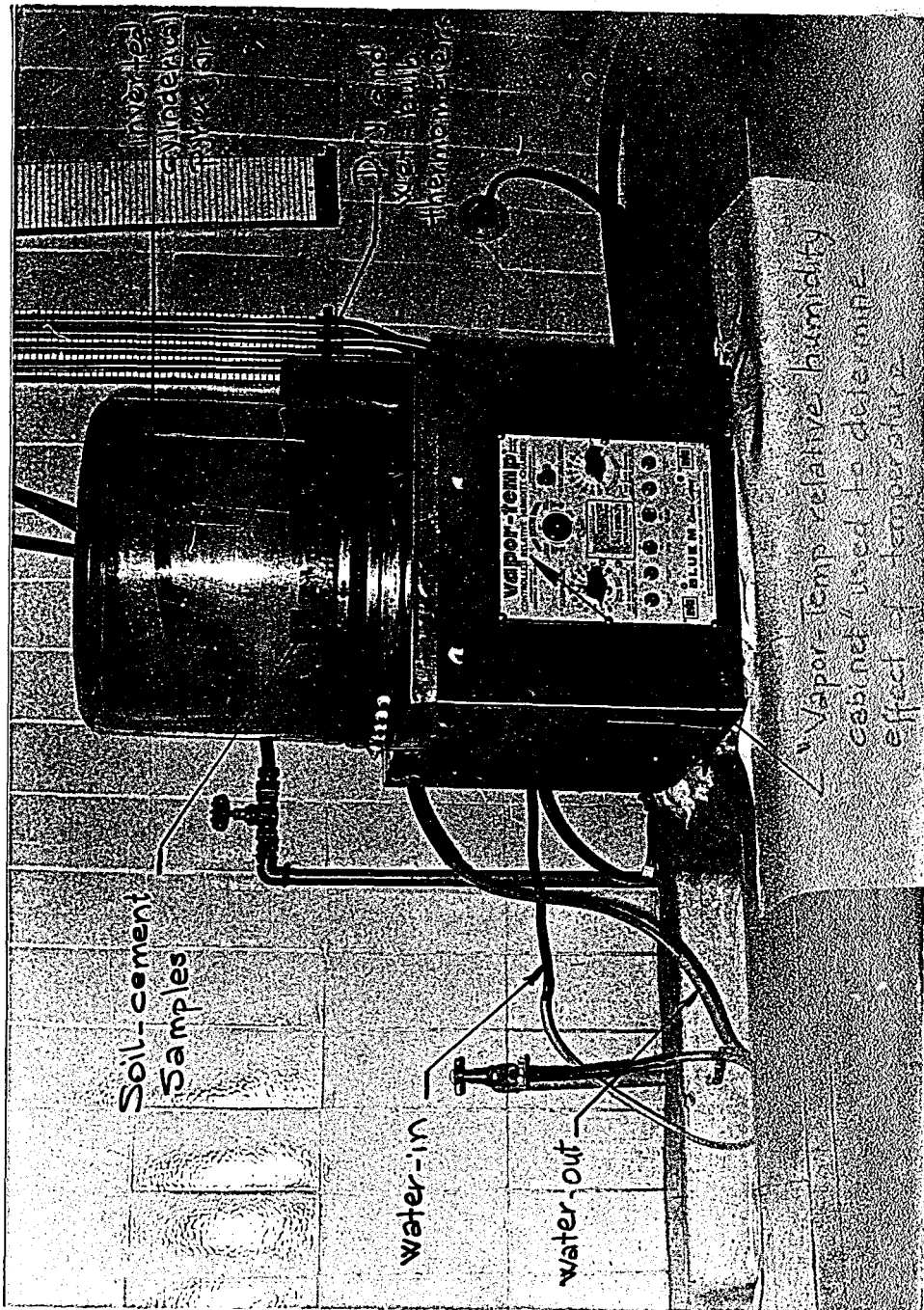


FIG.11- CURING: Curing of unconfined compressive strength samples to evaluate the effect of temperature.



FIG. 12— SOME OF THE SAMPLES AFTER TESTING

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