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EXPERIMENTAL INVESTIGATION OF SOIL FREEZING

BY

F. BALDUZZI

FROM

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TRANSLATED BY

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OTTAWA

1960

PREFACE

The work described in this publication from the Federal Institute of Technology in Zurich, represents an original approach to the problems of frost heaving in soils.

Dr. Balduzzi has observed the freezing and thawing processes in real and artificial soils, with a test apparatus allowing measurement of the significant factors of pore water tension, heaving pressures, and stress conditions in general. He made a detailed comparison of these observations with the behaviour of similar materials, under the conditions of triaxial stress developed in shear strength tests.

The Division has been actively engaged in research into frost action for some years, both in connection with highway and other construction in southern Canada, and also in connection with the phenomenon of permafrost. The relationship of this work with other soil mechanics studies has always been appreciated. Translation of this paper into English was accordingly felt very desirable.

The Division is grateful to Mr. Sinclair of the Translations Section of the N.R.C. Library for the translation.

Ottawa, R.F. Legget

September 1960

NATIONAL RESEARCH COUNCIL OF CANADA

Technical Translation 912

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Author: F. Balduzzi

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EXPERIMENTAL INVESTIGATION OF SOIL FREEZING

1. Introduction

The penetration of frost into the ground results in changes in its properties, the most obvious and most technically important of which consists in the increase of volume expressed in the form of frost heave.

An investigation of frost heave shows that in the majority of cases the underlying increase of volume is greater than that which can be attributed to the volumetric expansion of the water present in the ground.

Just as important a cause of frost heave lies in the displacement and accumulation of pore water or ground water in the vicinity of the frost boundary, where this water forms more or less coherent ice layers on freezing. The primary consequences of frost penetration into the ground are:

the separation (segregation) and movement (migration) of the water;

changes in the ground structure due to this separation and movement of the water and due to its expansion on freezing.

Secondary consequences of frost action are deformations of the ground and changes in its bearing capacity on freezing and thawing. To begin with, the latter has harmful effects on constructions built on such soils. If the structures suffer damage, this, along with other types, is referred to as frost damage.

Knowledge of these processes has hitherto been derived chiefly from studies of road damage, where both actual damage due to frost heave and apparent frost damage due to loss of bearing capacity during thaw can occur. The nature of the damage can seldom be determined definitely from such reports, but it is usually found that the seat of the underlying causes rests in fine-grained soils, or in coarse-grained or medium-grained soils if they contain fine-grained components.

No correlation can be established between the extent of the damage and its causes nor between certain climatic and topographical conditions and the causes of the damage, owing to the complexity of the factors involved. Experience to date can be more or less summed up as follows: "In the presence of an adequate water supply (ground or pore water) substantial frost heave may be expected wherever non-uniform soils contain more than 3% by weight particles of diameter less than 0.02 mm and wherever uniform unconsolidated soils contain more than 10% by weight particles of diameter smaller than 0.02 mm. In loose rocky soils with less than 1% by weight particles of diameter less than 0.02 mm, no ice growth was observed even when the ground water table lay within the frost limit."

The conclusions derived from this empirical evidence are widely applied in the testing of soils, in the form of the Casagrande criterion(1). So far, no observations have been made which contradict what has been formulated here.

Taber(2) investigated this phenomenon in the laboratory in order to determine what soils were responsible for the formation of ice. He succeeded in showing that the formation of intermediate layers of ice was clearest in cohesive and weakly cohesive fine-grained soils, but could not be detected in non-cohesive soils of medium or coarse grain. This was most strikingly demonstrated by Taber's experiment in which he studied the freezing behaviour of a cylindrical sample of which the cross-section consisted half of sand and half of frost-heaving soil (Fig. 1). On penetration of the flat "frost boundary" into the sample perpedicularly to the cylinder axis, definite intermediate ice strata form in the half consisting of frost-heaving soil and this results in an increase of volume perpendicular to the frost boundary. At the same time the sand half shows no perceptible change. Taber was also able to show that the increase of volume of the water on freezing is not essential for the formation of the ice lenses. He replaced the water by an organic liquid which does not expand on freezing and found that on penetration of the critical frost limit for this liquid into a cylindrical sample of frost-heaving soils interlayers of the solidified organic phase had formed just like the lenses. Beskow[3], Dücker[4] and Peltier[5] demonstrated in tests that freezing samples which communicate with a supply of water can under certain circumstances attract the water during frost penetration. However the regular relationships between water supply and frost heave in part suspected by these authors are already very hypothetical, as is the measurement of the capillary height of climb, attempted from time to time in these investigations or of the tension in the water. With this, all our established information concerning ground frost today is described, and all further laboratory investigations often very time-consuming, have thus far revealed no regularities of general validity and applicability, but have merely succeeded in confirming the mentioned empirically discovered facts.

Ground frost is clearly a complex phenomenon, the nature of which is by no means revealed by the experiences depicted above. From the need to get an understandable idea of it, however, certain hyptheses have been advanced which attempt to interpret at least the most obvious features of the phenomenon. The imagination has been stimulated most by the phenomenon of a water transport at the intermediate layer (ice lens), which explains why almost all pertinent hypotheses deal first with this problem. These are the theories of Beskow[3], Peltier[5] and Jumikis[6], all of which attempt to explain the value of the frost heave on the basis of a theory that takes into account the permeability of the material, the distance between the ground-water table and the frost boundary and a gradient (capillary height of rise, tension, etc.), and, depending on the particular problem, has the general form of Darcy's law. To test these hypotheses apparatuses for freezing tests were built, all of which are derived from a common prototype known as the Enslin apparatus (Fig. 2). In this setup a material sample for determining the water absorptivity in placed on the porous plate and either the amount of water absorbed is measured (valve 1 closed, valve 2 open) or with the Hg manometer, the water column with which the sample is in equilibrium (valve 1 open, valve 2 closed). To carry out the freezing test the sample holder is cooled, and the sample is either frozen through or a 0° isotherm is kept stationary within the sample (by means of separate thermostatic control of the lower and upper halves of the sample). Specifically, the following tests have been carried out:

1. Measurement of the capillarity (Beskow).
2. Measurement of the water taken up and the frost heave (Dücker, Peltier).
3. The same with the sample loaded (A.C. of Engineers, Jumikis).
4. The same with freezing and thawing cycles, on both natural soils and fractions of given grain size and petrographic character.

The results of these investigations, however, do not establish any regularities between the classification properties of the soils and their behaviour in the frost test, especially in the case of silty or clayey gravels. The only significant result of these tests lies in whether or not ice lenses were formed. As far as the tests with pure fractions are concerned it may be said that the soil-mechanics behaviour of a fraction taken from its natural association could not be representative of the general behaviour of the combination because it would not represent the decisive fraction.

The first and most basic criticism of the previously formulated hypotheses is that they take into account only the behaviour of the water and the ice. However, water and ice, as soil components, behave in more or less the same way in all soils, although the soils themselves react differently to the penetration of frost. Hence the essential criterion which will determine the behaviour of soils in the presence of frost must be a soil property and not a water property. Any relationship between the frost heave and water supplied can only exist if it be assumed that the ground experiences no other change in structure except that due to the formation of ice lenses. This assumption cannot be proved. In any case such a relationship between the frost heave and the danger of frost ignores the essential fact that certain soils form intermediate layers of ice without heaving. Furthermore any attempt at an explanation on the basis of capillarity must fail because ice lenses form even in soils which are capillary saturated or totally saturated, that is to say even in soils in which the capillarity as such can have no effect. All in all, therefore, any "hydraulic" explanation of ground frost appears unsatisfactory. In particular, it cannot explain the differences between frost-susceptible and other soils. Under any such hypothesis all soils would have to be termed frost-susceptible and would differ from each other in the extent of their susceptibility as a function of the transport distance, the permeability, etc. No final conclusions can be reached in this way, therefore, on the formation of ice lenses. The testing devices constructed on the basis of these hypotheses for the most part measure phenomena which depend on the test apparatus (frost heave and water supply) or processes which are not representative of the desired magnitude, e.g. the measurement tension of unsaturated samples.

In addition to the many discussions on the behaviour of the water and its supply to the ice lenses, data are to be found here and there in the earlier literature on the freezing behaviour of the soil. Taber observed the formation of cracks due to stresses in clays during freezing tests in which no additional water was supplied, if the water going into the ice lens was derived from the unfrozen part of the sample. Terzaghi(7) showed that the forces required to convey the water from the unfrozen ground to the ice lenses must be equal to the external pressures which are required in order to produce an equal change of volume in the unfrozen ground i.e., they must be very great. Casagrande(8) attempted to demonstrate this experimentally by determining the water content of the "unfrozen" clay remaining between intermediate ice layers and comparison with the water content-consolidation curve of the same materials. Unfortunately only one such test has been published, namely a frost penetration test, which however did not prove very much because the temperature gradient was not kept stationary for a long enough time in order to bring about complete consolidation of the material. In any case it was found that as a result of frost penetration pressures of the order of 4 to 8 kg/cm^2 could occur. In his tension hypothesis Ruckli[9], in order to explain the formation of ice lenses, has defined a suction force p which is claimed to be a specific soil coefficient. In order to determine this soil coefficient a measurement of the tension immediately below the ice lens is suggested. However, such a measurement could scarcely be carried out in this form. These observations lead to the only theorems which cannot be rejected a priori. Specifically they contain what is essential in order to distinguish between soils that are frost susceptible and soils that are not. Whereas by the "hydraulic" hypotheses, as already mentioned, all soils must in the last analysis be frost susceptible, the "soil-mechanics" approach leaves room for the possibility of distinguishing between two or more classes of frost-susceptible and non-frost-susceptible soils, and, provided the presumed soil coefficient has some real significance, a quantitative potential degree of frost susceptibility of a soil can be stated independently of all other factors. This possibility alone is sufficient to justify the implementation of further studies in the direction thus indicated.

The relationship between labour expended and the usefulness of results in frost research here and elsewhere is definitely poor. Early failures of an empirical, speculative procedure can be attributed to lack of knowledge about the principles of the phenomenon itself. This also means that the results cannot be interpreted on a common basis. We are just as far from solving the problem of the reasons for the formation of ice lenses as that of the extent of potential frost susceptibility of a soil. However, as long as there is no clarity concerning the mechanism of the phenomenon there is no possibility of influencing the process in any suitable manner.

The purpose of our study is to clarify the principles of the phenomenon of ground frost so that the potential degree of frost susceptibility of a soil can be determined and thus reasonable measures can be taken to prevent the effect of frost. This gets us further into the problem from the standpoint of both theory and measuring technique and takes us so far away from the representation and test technique based on models that in the course of the investigation the relationships between what is being investigated and practical solutions may not always seem as clear as a practical person might desire. The lack of even the most elementary data on the forces occurring in connection with ground frost and their effects on the soil compel us to consider the phenomenon at first as a whole, so that we may thereby find suitable starting points for an experimental investigation. For this purpose it is necessary to measure the forces which act in the frost phenomenon on ground and water, using the classical methods. This implies preliminary studies, first to find the conditions under which direct measurements are possible, and secondly to show that these conditions do not (neither the conditions themselves nor the measurements as such) influence the process under investigation. It is hoped that the results of this preliminary work and these first investigations will enable us to determine what soil properties are of decisive importance for frost behaviour and will permit us to study these properties more closely. Following a suggestion by Dr. P. Niggli, the studies begin with a monomineral material and are gradually extended to relatively homogeneous, representative soils.

The assumptions underlying the planning of this work and the view resulting therefrom concerning the process can be outlined as follows: The "hydraulic" point of view considers the ground frost as purely a question of water supply, the soil itself playing the part of a passive medium in which only a migration and a change of phase from liquid to solid on the part of the water takes place. As a logical consequence of this we get the heave measurement in order to determine the amount of the water supplied, the application of Darcy's law to determine the gradients responsible for this supply, and finally the attempt to classify the soils as to frost susceptibility on the basis of their permeability properties. The only soil coefficient which can be taken into account in this is the permeability. Even consideration of the capillarity is based on a supplementary, unproved assumption. The only available measurements have to do with the amount of water supplied or the extent of the heave, since it is assumed that there is a correlation between the heave and the quantity of water available.

In what follows, however, the ground will be treated as the bearer of the ground frost phenomenon, although this occurs solely on the penetration of frost into <u>certain</u> soils, the particular character of which is to be characterized as a function of their soil coefficients. At the same time, for the case of frost penetration in general and the occurence of ground frost in particular, the state of the soil is naturally changed. Two principal problems must therefore be given special attention:

What characterization of the soil is logical and useful for considering its frost properties?

What forces are involved in the penetration of frost into the ground?

Thus we shall be interested primarily in the measurement of the forces which act on the ground on penetration of the frost - i.e., the heaving pressure instead of the heave, the pressure in the liquid phase (pore water) instead of the water consumption - for characterization of a soil, the determination of its mechanical strength properties instead of its permeability (classical property) and further, the determination of the state of the soil before and after penetration of the frost. While some of these measurements can be carried out with known means, most required development and testing from both the theoretical and the practical standpoint for the purposes of this study.

From our previous knowledge of ground frost we can first distinguish between those soils which heave on the penetration of frost and those which do not. Laboratory investigations also enable us to divide soils into those which show the formation of ice lenses and those which show no such formations. There is no correlation between the two criteria, so that to begin with we have three classes of soil:

heaving - ice lens forming
not heaving - ice lens forming
not heaving - not ice lens forming

The not heaving, not ice-lens-forming soils can be subdivided further into soils with and without storage of water.

The order of magnitude of the forces occurring on penetration of frost into a soil sample can most easily be determined by measurement of the heaving pressure. This can be carried out with heaving, ice-lens-forming material. With free lateral expansion it is executed perpendicularly to the direction of the force and the stationary temperature gradient in the direction of a force is so chosen that the 0°-isotherm is inside the sample. The unfrozen portion is in communication with a supply of water. For a cylindrical sample, on this basis, we get the test arrangement shown in Fig. 3: the sample stands on a filter plate heated to 10°C, which guarantees the supply of water from a reservoir; the sample is prevented from expanding axially upwards by a balance. The force just required to prevent this expansion on penetration of the frost is measured. The determining factor in this is the constant value which sets in when the position of the 0°-isotherm in the sample is steady. The execution of such a measurement on a test material shows that forces of the order of 10 kg/cm^2 can occur. With free expansion in all directions, but the water supply shut off, a tension of the same order of magnitude in the liquid phase may be expected. Since a measurement of the tension is only possible if the liquid phase forms a continuum, and then only if no cavitation occurs, a few special problems of a technical and fundamental nature arise in connection with this task. The requirement that the liquid phase must constitute a continuum can only be satisfied if the measurements can take place within a saturation region which is in contact on the one hand with the measuring probe and on the other with the ice lens. (A saturation region is defined here as that part of an unsaturated soil sample inside which the liquid phase is continuous, and the boundary surface of which is in contact only with a gaseous phase or a particle of the soil). In an unsaturated soil, however, the dimensions of the local saturation regions are not known. The only feasible solution for the measurement of the tension in the local saturation region of an unsaturated sample therefore consists in so increasing the saturation region that it embraces the entire sample (i.e., the measurement of the tension is carried out in the two-phase system soil/water). For this, of course, it must be demonstrated that in the two-phase system the same forces act as in the local saturation region of the unsaturated samples, both for the case of processes during the penetration of frost and for the mechanical properties of the samples which determine this. Such a demonstration is equivalent to saying that in the three-phase system of the ground, the gaseous phase (air) is incidental (Ruckli), i.e., all the phenomena that occur only in the presence of the gaseous phase are of secondary importance or constitute mere interferences with the process under consideration. This applies among other things to the "capillary component" of the cohesion of soils and the "capillarity" of soils to which importance is attached by various authors in explaining the ground frost. The requirement that no cavitation be permitted to occur in the liquid phase sharpens the already well-founded requirement that the system under investigation shall in its initial state constitute a two-phase system; this must remain during the entire measurement regardless of the pressure region which must be passed through. From what has been stated here it follows that the effects of frost penetration (for the class of heaving, ice-lens-forming soils) can be determined in the case of unsaturated samples only by measuring the heaving pressure, and in the case of saturated samples by measuring both the heaving pressure and the tension which acts on the liquid phase (or more generally the pressure which occurs in the liquid phase). If we are to determine the ground frost phenomenon in its entirety this measurement cannot be avoided. A description of how it is carried out will therefore constitute the first part of the present paper.

From what has been said above the following working plan recommends itself:

1. Production of saturated samples of soils and determination of their saturation;
2. Effect of saturation on the mechanical properties of soils and measurements thereof at saturation;
3. Execution of freezing tests from saturated samples accompanied by measurement of the pressure in the liquid phase;
4. Measurement of other frost properties of the soil.

The monomineral material for the first test should have the following properties: it must be inert, be of a grain distribution similar to natural materials, be accessible to wetting and on penetration of frost be able to form ice lenses; in addition it must meet all demands with respect to workability and economy. After examination of available materials it was found that titanium dioxide of the type used as a pigment was suitable for the purpose. The material no. 6618 consisted of isodiametric grains of anatase with 1.2% rutile*.

Other test materials are: homogenized Uetliberg loam 4002 of VAWE, a clayey silt representative of Swiss conditions and a naturally occurring pure silt 8699 from Sufers. Finally, in order to test the effect of saturation on the mechanical properties alone a structurally sensitive material - undisturbed marine chalk 7071 from Lake Zurich - was used, which is regarded as particularly sensitive to manipulation. The classification of these materials is shown in Table I.

2. Determination of the Shearing Strength of Saturated Soils

A natural or artificially prepared soil sample consists of a solid phase (the soil), a liquid phase (the water) and a gaseous phase (the air). In the natural samples the proportion accounted

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* These data are taken from investigations which were kindly carried out by Dr. Hochweber and Dr. Preis of the Eidgenossische Material-Prüfungsanstalt.

for by the gaseous phase may vary considerably owing to special circumstances, but this can also occur in the artificial samples as the result of special manipulations. Only in very rare cases, however, will this component disappear entirely. A great many suggestions have been made in order to obtain completely saturated soil samples. It can be stated, however, that neither the forcing-through of liquid (even under pressure), nor consolidation over many years, nor sedimentation under water are sufficient to enable this goal to be completely achieved.

The same is true of the "chemical" methods which replace the air, prior to wetting, by a more water-soluble gas. This method, however, does suggest another possibility. Instead of replacing the air by a soluble gas, the solubility of the air itself may be increased by pressurizing the water. This compression, which is attainable on the basis of the laws of Boyle and Henry, and the dissolving of the air can be achieved, for the practical case of a soil sample, in two different ways:

1. The soil sample can be closed in a watertight and airtight manner by a membrane and then deformed by the application of pressure in all directions until any further increase of pressure produces no further change of volume of the sample. A measurement of the pressure of the liquid phase in the sample (pore water) shows that a further increase in the cell pressure corresponds to an equal increase in the pore water pressure (i.e., that the effective state of stress does not change any further).

(If

σ is the total normal stress on a plane,

σ' the mean grain-to-grain pressure per unit area, i.e., the effective stress,

u the hydrostatic pressure in the liquid phase, which from now on will be termed the pore water, and

a_r the effective grain contact area per unit area, then

$$\sigma = \sigma' + (1 - a_r)u \qquad (1)$$

If $(1 - a_r) \sim 1$, then equation (1) is simplified to $\sigma' = \sigma - u$.

If $C_c = -\frac{1}{V} \cdot \frac{\Delta V}{\Delta \sigma'}$ the compressibility of the soil and

$C_u = -\frac{1}{nV} \cdot \frac{\Delta V}{\Delta u}$ that of the pore water and

n the porosity of the soil, then $\Delta\sigma' = n \cdot \frac{C_c}{C_u} \cdot \Delta u$ must hold, with $B = 1/\left(1 + n\frac{C_u}{C_c}\right)$, $\Delta u = B \cdot \Delta\sigma$,

where, at saturation, B = 1 (according to Bishop and Eldin[10].)

In obtaining saturation in this manner, it must be borne in mind that the sample is at the same time being deformed and saturation exists only beyond a certain value of the cell pressure, depending on the original degree of saturation.

2. The soil sample can also be saturated by closing it off hermetically with a membrane and connecting it to a source of water the pressure of which is initially equal to the cell pressure against the sample. In this case, if the cell pressure and the pressure of the water source connected to the pore water are together raised by a certain amount depending on the initial degree of saturation of the sample, then saturation of the sample can be obtained without its deformation. Whether saturation prevails or not can be determined by discovering the increase of pore water pressure corresponding to an increase in the cell pressure, at constant water volume (B-factor) (cf. Bjerrum and Huder[11]). A practical embodiment of the method is represented in Fig. 4. Sample 1 is installed in a compression cell and connected to a water tank 2. Tank 3 is connected to the liquid surrounding the sample in the compression cell.

Among the mechanical properties of soils the shearing strength is the one which is most sensitive to the test conditions. For certain conditions, of course, the shearing strength is defined as the maximum shearing stress that a sample is able to withstand. The investigation of the shearing strength consists generally in an analysis of the effect of the cell pressure, the rate at which the load is increased, the change of volume and the pressure in the pore water, on the strength of the soil (Skempton[12]). For this purpose triaxial shearing tests are used. For the purposes of the present paper the consolidated, undrained, cylindrical pressure test is used in which the first principal stress acts in the axial direction on the sample, the second is chosen equal to the third and these two are given by the hydraulic cell pressure. The soil sample is insulated from the environment by a membrane, it is installed in a compression cell and connected by a porous plate to a water reservoir. For consolidation (i.e., for the adjustment of the volume and water content corresponding to a given cell pressure) the line to the water reservoir is open and the sample is drained. After consolidation is complete the line is closed and thereafter the pressure test is carried out at constant water volume. The pressure in the pore water is measured at constant volume by means of a compensation manometer. The cell pressure is measured with a manometer, the supplementary axial load with a ring balance and the axial deformation of the sample with a dial gauge.

The first test material used was TiO_2 6618 (see above). The size of the sample was the same in all tests and the deformation rates were the same in the first four tests. The cell pressure is determined in advance. The following quantities are measured:

σ_3 in kg/cm^2;
$\sigma_1 - \sigma_3$ in kg/cm^2;
the deformation in cm and
the pressure in the pore water in kg/cm^2.

From these measurements the effective state of stress corresponding to each deformation can be determined and represented in a Mohr circle diagram. The increase of load and change of pressure in the pore water can be represented by stress-strain diagrams. However, the analysis of the test results is facilitated by using a representation introduced by Casagrande, termed a vector curve. This representation takes into account simultaneously, for each state of deformation of the sample (from the start of deformation to fracture), the cell pressure, the supplementary axial load and the pressure in the pore water. This is achieved by describing the course of the resultant vector of the effective normal stress and the effective shearing stress in the $(45° + \phi/2)$ plane with a curve which joins the terminal points of all vectors (from the initial state of the sample to the end of the test). The construction of the vector curve for each test is evident from the representation in Fig. 5a-e. Fig. 5a shows the resultant vector of a state of stress, Fig. 5b the resultant vectors of all the states of stress passed through during a test in the plane of fracture, Fig. 5c the vector curve obtained for this for a typical test. By taking into account the effective stresses, the changes of volume of the pores are implicitly determined as a function of the state of stress and the degree of saturation of the material. For example, if the supplementary axial load up to fracture produces no change of pressure in the pore water (Fig. 5d), then the effective cell pressure remains constant and the vector curve is accordingly a straight line. On the other hand, if the supplementary axial load produces a change of pressure in the pore water for each state of deformation then the effective cell pressure will also change, and if the ratio of change of pressure in the pore water to the increase of axial load be termed the pore water stress parameter, $A = \frac{\Delta u}{\Delta(\sigma_1 - \sigma_3)}$, then the following result is obtained. The parameter A depends, at complete saturation, only on the material properties. To every change of A there will correspond, at saturation, a change in the deformation properties of the material or, at a certain degree of saturation, a change in the deformation properties <u>and</u> the degree of saturation of the material. The influence of the degree of saturation on the vector curve is expressed in a departure of the latter from the rectilinear course; similarly, any change in the deformation properties of the material, which are dependent in turn on the degree of saturation. Therefore, the general form of the vector curve of an unsaturated material has an appearance like that of Fig. 5e. The variation of A between zero and unity depends on the degree of saturation of the material, the latter being varied by the increase of pressure in the pore water until saturation is attained. Between one and two, A is affected only by the deformation properties of the material structure. Between two and three (after the occurrence of fracture) A depends on the deformation properties of the material and the degree of saturation, the latter varying in turn as a function of the reducing pressure in the pore water. Hence, the representation of the triaxial shearing test in the form of a vector curve constitutes a description of the deformation properties of the material and therefore also of its structure, these properties depending indeed on the degree of saturation, and also taking the degree of saturation itself into account.

In our tests for determining the shearing strength, therefore, the case of less than 100% saturation must be distinguished from that of saturation itself. In the first case it must be borne in mind that for every deformation and change in the state of stress of the material a migration of the liquid phase occurs. This migration is expressed in an increase or reduction of the local saturation zone, depending on whether the pressure in the pore water increases or decreases. These changes in the boundaries of the saturation region correspond to changes in the local water content of the sample. The rate at which they occur is determined by the permeability of the material and the area of the saturation zone. For each change in the state of stress, the state of equilibrium is attained when the stresses of all local saturation zones are the same. The dependence of this process on the time, for continuous deformation at a constant rate, can be determined by investigating the relationship between the deformation properties and the rate. At saturation, on the other hand, the deformation properties of the material must be independent of the rate of deformation.

Tests with TiO_2 6618

The first three tests to determine the shearing strength in unsaturated TiO_2 are summarized in Fig. 6a. Similar samples of this material were consolidated at cell pressures of 2, 6 and 12 kg/cm^2 and were loaded at equal pressures until failure. The vector curves of the experiment for 2 and 6 kg/cm^2 show basically similar behaviour, while that of the test at 12 kg/cm^2 shows the strong influence of the degree of saturation of the sample on the test curve. A fourth test was conducted in which the first-mentioned method of producing saturated samples was applied. After consolidation at 6 kg/cm^2 the cell pressure was increased until $\Delta u = \Delta\sigma_3$, and after reaching the state of equilibrium (at the then resulting cell pressure of 9 kg/cm^2 - effective cell pressure 7 kg/cm^2) the sample was loaded until failure occurred (Fig. 6b). This result confirms the above views on the effect of saturation on the course of the experiment and permits formulation of a plan for a series of tests to examine the phenomenon systematically. That is to say, our experiment is to show that in the two-phase system soil-water in which the elementary saturation zone involves the entire sample, its deformation properties are independent of the loading or deformation rate. For this purpose three tests were carried out under otherwise similar conditions at rates of 10, 100 and 1000 min/cm. The results of these tests are summarized in Fig. 6c and, within the limits of accuracy they do in fact yield the desired proof. In addition to this result examination of the vector curve shows the following: it consists of three sections, each of which is characterized by a certain stress and strain. To explain the first two sections certain assumptions have to be made concerning the structural and compressibility properties of the material. In the present paper we are chiefly interested in the character of the material after failure, in which condition only the friction properties are still effective. The change of volume after failure of the material under shearing stress depends, according to the vector curve, solely on the angle ϕ of the shearing strength. At the same time this gives us a new criterion of failure that may also be made useful in the general investigation of the shearing strength. The other tests on the dependence of the material properties on the cell pressure have all been carried out at the lowest deformation rate (1000 min/cm) of the previous test series. Fig. 5c shows that investigation of the shearing strength in the two-phase system at saturation gives the same angle of the shearing strength as in the investigation in the three-phase system (i.e., the extension of the elementary saturation zone to the entire sample has no effect on its shearing strength). As expected, the tests at complete saturation can be carried out at any rate of the change of state without thereby affecting the material property being investigated. This fact is partioularly important in connection with tests accompanied by a change in the thermal state. It must still be determined, of course, whether these results have general validity and are characteristic for each material.

Tests with Typical Soils

To clarify this question it was necessary to apply the same determination of material properties to the soil samples, i.e., clayey silt 4002 and marine chalk 7071. The results of this investigation are given in Fig. 6e and 6f. The test results show that the vector curve does in fact give a suitable description of the material properties and enables us to give a positive answer to the question posed above: the vector curve of a material investigated at saturation generally speaking reflects its volumetric behaviour under stress, while the rate of change of states, generally speaking, does not affect the determination of the shearing strength. Consideration of the part of a vector curve which corresponds to the deformation of the sample after failure results in the following. While TiO_2 6618 on further deformation at a constant rate shows an increase of pore volume - and an increase in the effective cell pressure due to decrease of pore water stress - which corresponds to an increase in the axial load, the extremely sensitive marine chalk displays precisely the opposite behaviour, since on deformation at a constant rate a reduction of the pore volume sets in - accompanied by a decrease in the effective cell pressure due to the increase of pore water stress - and a corresponding decrease in axial load. In both cases, however, the vector curve shows the same tendency with respect to the angle of shearing strength. The silty clay 4002, on deformation at constant rate after fracture, shows constant pore volume, i.e., constant effective cell pressure and pore water stress, to which a constant axial load corresponds. In this case the vector curve degenerates to a point: the material is deformed plastically. In general we may distinguish between two classes of material, namely dilatant and plastic. In the dilatant materials there is grain-to-grain pressure and after breakdown of the structurally determined strength the deformation takes place here through relative displacement of the grains, resulting in either a looser or closer packing. In the plastic materials, on the other hand, the deformation after fracture proceeds at constant pore volume. This is only possible if the fluid shell around each individual grain, being completely without shearing strength is closed, i.e., if there is no grain-to-grain pressure. Only under these conditions can the individual grains change their relative positions without at the same time altering their area of contact (which is and remains here equal to zero; in all other cases displacement is associated with a change of area of contact and consequently a change of pore volume).

3. Determination of the Frost Properties of Saturated Soils

The planning of our frost tests is based on the experience of other authors, as mentioned in the introduction, as well as our own studies. For convenience, cylindrical samples have been used in the majority of the test arrangements where the temperature gradient in the direction of the cylinder axis is stationary or non-stationary. In the literature various arrangements of side insulation or controlled side cooling are described, all of which have the purpose of maintaining a 0°C isotherm plane perpendicular to the cylinder axis. The tests conducted for the purpose of the present work show that in a cylinder of which the length is twice its diameter, the 0°C isotherm, even without additional insulation or controls, constitutes a plane perpendicular to the cylinder axis (it is advantageous, therefore, to dispense with these, because they delay the attainment of a state of equilibrium). Accordingly, we have the test setup illustrated in Fig. 7a. If a clear measurement of the pressure in the pore water is obtainable only with a completely saturated sample, then the occurrence of a tension requires additionally that the entire range of pressures covered shall lie within the saturation region. This can be realized by applying, in addition to the hydrostatic pressure on sample and pore water, a prestressing of the pore water equal to the expected pressure difference and imparting this to the sample itself as well, in order to keep the effective state of stress constant. Because the value of the occurring tensions is at first unknown the chosen prestressing may prove inadequate in individual tests. In these cases the tests with comparatively large prestressing should be repeated. All this leads to the following procedure: the sample is installed in a pressure cell similar to the one used for conducting the shearing strength investigation. The apparatuses for measuring the pore water stress, the cell pressure and for producing the supplementary pressure for saturation of the sample remain the same. Of course, the fluid by means of which the cell pressure on the sample is produced is changed - alcohol instead of water - and in addition, an apparatus is installed to cool the upper half of the sample and one to heat the lower part. Cooling and heating are separated by a porous foam rubber diaphragm; no provision is made for temperature measurement within the sample because this would disturb the process (Penner[14]) and in any case it is only necessary to know that the frost boundary lies within the sample. The only consequence of a change of temperature gradient is a displacement of the frost boundary. Fig. 7b shows the frost test apparatus schematically. The practical execution of the frost test takes place in three stages:

consolidation of the material;
saturation of the sample;
the frost test itself.

The actual frost test begins when the upper part of the consolidated and saturated sample is cooled while the lower one is kept at constant temperature. Simultaneously, the axial deformation or the heaving pressure, and the pressure in the pore water or the consumption are measured. Hence we get the arrangements in Fig. 8a, b, c, d, which are as follows:

(a) Measurement of the deformation and the water consumption, free axial expansion, free water movement (drainage open).

(b) Measurement of the heaving pressure and the water comsumption, axial exoansion prevented, free water movement (drainage open).

(c) Measurement of the pressure in the pore water and the deformation, free axial expansion, constant water volume (drainage closed).

(d) Measurement of the heaving pressure and pressure in the pore water, axial expansion prevented, constant water volume (drainage closed).

Finally, a thawing test was to determine the change in the state of the material due to freezing and thawing. However, since it was found useful to investigate the frozen state of the sample as such, thawing tests were included only as exceptions within the scope of the present work.

Tests with TiO_2 6618

Simple tests had shown that this material is subject to formation of ice lenses and heaving on penetration of frost. As an initial extension of the test technique developed by Taber, the heaving pressure in this material was measured on an unsaturated sample for the freezing test in the open system. The results of the test, shown in Fig. 9a, revealed a heaving pressure of 7 kg/cm^2. A check of the water content of the unfrozen part of the sample with the water content-consolidation curve of the material gave the same result. The other tests, the results of which are contained in Table II, were carried out at complete saturation. Determination of the pressure in the pore water for free axial deformation and constant water volume in test 6 showed a tension in the pore water of 6.9 kg/cm^2. From a comparison of the results of the test in the unsaturated state (Fig. 9a) and test No. 6 the following basic conclusions may be drawn:

The tension in the pore water for free axial deformation and constant water volume is equal to the heaving pressure for free water migration.

The forces which occur in the elementary saturation zones are independent of the size of these zones. As a special case, the saturation zone may involve the entire sample.

At the same time, however, other questions arise, especially the following:

Does the tension depend on the prestressing in the pore water? (The heaving pressure does not!)

What is the connection between the heaving pressure and the pressure in the pore water?

What happens on thawing?

On the basis of tests 3 and 4, which were carried out with various prestress values superimposed on the cell pressure and the pressure in the pore water, the first question can be answered in the negative. The second question is answered by tests 3, 4, 6 and 16 in which axial deformation was prevented at constant water content. These tests show that the measured tension in the pore water is less in these tests than in the tests with free axial deformation by an amount equal to the heaving pressure. The two forces behave additively, which means that the state of stress in the unfrozen part of the sample caused by the penetration of the frost is always the same, regardless of the test arrangement. The last question is decided by test 6, where, after attainment of the state of equilibrium and determination of the pressure in the pore water the cooling was shut off. The deformation did not merely reverse itself, but the sample showed an additional settlement of 0.5%. At the same time, the measurement of the pressure in the pore water showed a superpressure equal to 82% of the effective cell pressure. This by itself is enough to destroy the bearing capacity of the sample (what is surprising is the fact that apparently a single freeze-thaw cycle is sufficient to bring about this state). From the actual TiO_2 freezing tests, therefore, it follows that direct measurement with classical methods can provide information which goes beyond our experience without contradicting it. The sufficiently tested measuring methods themselves are now to be applied to the other selected test materials.

Tests with Silt 8699

The first of the natural materials to be investigated was silt, a material which is well known and feared as a frost-susceptible foundation material. For the classification characteristics of the naturally occurring material of our test see Table I. The vector curve of the material indicates a dilatant one. For the first test (No. 9) which is represented in Fig. 9b, the sample was not consolidated under cell pressure, but anisotropically, at a certain relationship between vertical load p and side pressure $k \cdot p$, where $k < 1$. The freezing test was afterwards carried out at constant water volume and with axial expansion prevented. The test showed that after the occurrence of a small tension during penetration of the frost in the steady state a <u>pore water superpressure</u> sets in. At the same time the unfrozen part of the sample under the constant vertical load at which it was consolidated collapses as soon as the pressure in the pore water rises.

This unexpected result was verified by tests 10, 11, 17 and 22a (see Table III). For this purpose the arrangement with the blocked axial expansion and constant water volume was employed. The superpressure measured in these tests was between 60 and 90% of the effective cell pressure. The drained tests (13, 14a and 15) in which the pore water was forced out during penetration of the frost served to confirm the discovered fact. Examination of the samples in the frozen state showed that in no case was there any formation of ice lenses. The determinations of water content showed that a migration of water takes place from above downward at the frost boundary. The only possible conclusion from these results therefore is that in these non-cohesive soils the pore water is forced downward from the freezing into the unfrozen layers during frost penetration. Since fine sands and especially silts, among non-cohesive materials, are very sensitive to changes of water content the consequences of this phenomenon, namely the reduction in the strength of the material in the unfrozen layers, are obvious. A single field observation of N. Goldstein so far confirms this fact:

"The effects of (water) migration in cohesive and non-cohesive soils are different. When cohesive soils are frozen the moisture is always attracted to the frost boundary. <u>In non-cohesive soils it appears as if on freezing the moisture were forced to recede before constantly growing ice crystals</u>. This makes it possible to use sandy soils as barriers to the flow of water towards the frost boundary." (In the literature which is influenced by representation of the effect of "capillarity" during penetration of the frost this same layer is called "capillary breaking", and it is possible that this false idea has made correct observation of the phenomenon more difficult.)

In the first of the materials investigated, TiO_2, a migration of the water from the unfrozen part of the sample to the frost boundary was clearly demonstrable. The tests with silt 8699, on the other hand, showed that water from the frozen layers is forced downward into the unfrozen part of the sample. To explain this divergent behaviour it must be assumed in the case of TiO_2 that the penetration of the frost brings about changes in the structure of the sample which are expressed in an increase of pore volume, if only to provide room for the water present which is freezing, and hence expanding. This structural change, already taking place during the rapid penetration of the frost may be the reason for the well-defined ice lenses forming in the stationary state. In the case of silts, however, <u>no</u> such change of structure of the soil takes place during freezing, for which reason here also the growing ice crystals can force the water downwards. Whereas in the case of TiO_2 the unfrozen part of the sample consolidates and the destruction of the strength during thawing in the previously frozen part of the sample is caused by the superpressure in the pore water, in the case of silt the collapse of the strength must be attributed to the properties of the unfrozen part of the sample, i.e., its sensitive reaction to changes of water content, and no change in the properties of the frozen part of the sample can be attributed directly to freezing.

Tests with Clayey Silts 4002

On penetration of frost this material, both in laboratory tests and in the field, shows clear formation of ice lenses, without any manifestation of heaving pressure. For this reason small or zero tensions are to be expected in the pore water in freezing tests with free axial expansion and constant water volume. The results of tests 40 and 41 (Table IV) do in fact show a sub-pressure in the pore water of only 0.2 kg/cm^2. This finding must be reconciled with the observation that the material forms ice lenses. However it must first be determined whether or not the sub-pressure in the pore water depends on the consolidation pressure, i.e., on the state of the material. Tests 42 and 43 reveal that any such relationship in only very insignificant. It is evident from these tests that the formation of ice lenses and the tension in the pore water are not directly associated. Therefore, if ice lens formation is a necessary condition for the occurrence of a tension, nevertheless it cannot account for it completely. Rather, other conditions which depend on the medium in which the freezing occurs, must be satisfied. On the other hand, precisely this ice lens formation points to a radical change in the structure of the soil as a consequence of the penetration of the frost, which can occur even without (or with only slight) migration of water from the unfrozen part of the sample.

Change of Soil Structure During the Penetration of Frost

In order to verify directly the structural change of the soil during freezing, which was assumed in explanation of the previous freezing tests, the following method was applied: a number of samples of the three materials investigated were prepared either with a Proctor apparatus or by consolidation in a large odometer and were subjected to a pressure test with unobstructed lateral expansion. The results obtained are compared with the results of samples with the same materials prepared in the same manner but which had passed through a freezing and thawing cycle prior to being tested for compressive strength. This freezing and thawing cycle consisted of the following:

Rapid freezing throughout of the sample protected by a rubber sheath in an alcohol-dry ice bath with a temperature of -70°C, and

slow thawing at a constant temperature of 20°C.

The samples are frozen under these extreme temperature conditions so that during the freezing process, which here occupies only a few minutes, no migration of the water can take place. The results of the compression tests are contained in Table V.

The tests reveal very sharply the different effects of frost penetration on the three materials investigated. The most significant results came from the silt test, but here it is evident that the freezing and thawing cycle may also be without influence on the state of the material, a result which reinforces the conclusions from the other two series of tests. The reduction of compressive strength in the case of clayey silt 4002 and in the case of TiO_2 is such that it must be regarded as an essential change. The change from the unfrozen to the frozen state takes place here, unlike the preceding freezing tests, in such a short time that no migration of the water over large distances can have been possible.

It can be concluded from this that the structural change is a locally restricted one which can only involve the particles in the immediate neighbourhood of each region of influence. This fact points to a coagulation process[16] in which previously bound water that was repelled by the solid soil components, in association with a simultaneous structural change of the soil, itself reduces the compressive strength of the soil. This confirms our conclusion, drawn from the results of the freezing tests, that in materials which form ice lenses on penetration of frost, rapid penetration itself brings about a structural change which, in the case of a slowly progressing or stationary freezing boundary, becomes the obvious structural change of the ice lenses.

It must also be remarked that the results contained in Table V are of a purely qualitative nature. The water liberated owing to a change of soil structure and coagulation does of course affect the compressive strength of the samples. The values measured are at least a qualitative proof of this reaction of the soil to the rapid penetration of the frost.

4. Discussion of the Results

Our tests were in all cases carried out in three steps:

Saturation of the sample

Investigation of the effect of saturation on the shearing strength of the samples

Investigation of the freezing of saturated samples.

The materials investigated have been chosen here for their particularly interesting properties, e.g. TiO_2 and the marine chalk, or their typical properties, e.g. the silt and clayey silt. Although the experimental basis is a restricted one, some of the conclusions to be drawn from the results, and in particular those which relate to the methods of investigation, are of general validity. The other conclusions, however, which point to the properties of the materials apply for the present, strictly speaking, only to the materials investigated; as qualitative indications of the behaviour of various kinds of soil, in the meantime, even these latter conclusions can be extended to all soils belonging to the same classes as those investigated here.

The first and most important conclusion is that it is possible to measure the forces acting on the soil and the pore water at saturation during the penetration of frost, while at the same time it has been demonstrated that the forces acting in the saturation zones are independent of the size of the zones bounded by the soil components and macropores (the point of view explained at the beginning and confirmed by the investigation concerning the role of saturation in the testing of the shearing strength and in the freezing tests of soils is supported by the investigations of T.C. Powers[17] and by T.C. Powers and R.A. Helmuth[18] on freezing tests with concrete and cement: there too, the total degree of saturation of a sample is not regarded as a valid measure of the decisive saturation occurring in local saturation zones). The methods based on these tests make possible the general investigation of the frost properties of the soil. A further possibility is also gained of developing ways of influencing these properties in the laboratory either by changing the properties of the soil components (e.g. by increasing the cohesion with cement) or by partial substitution of the fluid phase (e.g. stabilization with oil).

The second conclusion is that a relationship exists between the volumetric properties of the soils when subjected to shearing stress, as described by the vector curve, and its behaviour on penetration of the frost. The application of the vector curve for characterization of a soil-water system offers decisive advantages over a characterization by classification properties alone. This is particularly true in view of the division into materials which are deformed plastically and dilatent ones, made possible by the vector curve.

The tests with TiO_2 6618 and clayey silt 4002 as well as silt 8699 show that on penetration of the frost the forces acting on the soil and pore water are together determined by the characteristic properties of the soil, an hypothesis that was formulated at the beginning. They give information concerning the formation of ice lenses which in the materials under investigation are caused by the instability of the soil structure in the presence of the penetrating frost.

The two studied materials which form ice lenses, i.e., TiO_2 and clayey silt, for the first time permit a relationship between heaving pressure and tension in the pore water to be demonstrated. It was found that heaving pressure and tension in the pore water behave additively, i.e. that when either a heaving pressure (deformation prevented) or a tension (water supply prevented) occurs, or both at the same time, the forces acting on the unfrozen part of the sample are always of the same magnitude.

The tests also enable us to state that the formation of ice lenses may be caused either by migration of water from the unfrozen strata (in our case in the dilatant TiO_2) or by separation of pore water in the freezing strata (in the plastically deforming clayey silt). The measured tensions in the pore water (large in the case of TiO_2, vanishingly small in the case of clayey silt) confirm this fact and show that obviously the formation of ice lenses is a necessary, but not in itself a sufficient condition for the occurrence of a tension and a consequent migration of pore water. The fact that the tension is so great in the dilatant material TiO_2 and is vanishingly small in the plastic clayey silts, leads to the establishment of a relationship between the occurrence and magnitude of the tension on the one hand and the volumetric properties in the presence of a shearing stress on the other. The tests with silt 8699 led to the at first surprising result that on penetration of the frost into this material the pore water is forced out of the freezing stratum into the unfrozen, a behaviour that can be explained by assuming that the silt, already being of sandy character, possesses a structure which is proof against freezing. It thus becomes possible that water is forced out by growing ice crystals, a phenomenon which must be attributed to all soils with frost-proof structure (i.e., sands and gravels). In the case of the most fine-grained of the frost-proof soils investigated, i.e. the silt, its sensitivity to changes of water content leads to the conclusion that this material collapses due to loss of bearing capacity in the unfrozen strata as soon as the frost penetrates. This explanation does not conflict with the behaviour of the coarse-grained frost-proof soils, which, moreover, are insensitive to changes of water content. Obviously the latter fact alone would explain their insensitivity to the penetration of frost.

The problem of frost susceptibility of the soils can be interpreted generally with the concepts of frost-proof structure and sensitivity to changes of water content. While sensitivity to changes of water content is a problem of soil mechanics related to the order of magnitude of the specific grain-to-grain pressure and can be explained by consideration of the geometric properties of the soil (particle size and grain distribution), the frost-proof character of a soil is also related to its petrographic nature and the condition of the system in question, and is thus a problem of the coagulation properties of a soil falling within the scope of soil physics.

To sum up, the criterion of frost-proof quality enables us to distinguish between the soils which form ice lenses on penetration of the frost and soils which do not display this phenomenon. The soils which form ice lenses can be further subdivided by measurement of the heaving pressure into soils in which a migration of pore water takes place from the unfrozen strata to the frost boundary, and soils in which the ice lenses are formed predominantly by separation (segregation) of pore water. This subdivision is in agreement with that based on the plastic or dilatant character of the soil.

The criterion of sensitivity to changes of water content further enables us to single out those soils which, despite their frost-proof structure, suffer a loss of bearing capacity owing to this sensitivity and the forced recession water from the freezing strata into the unfrozen ones on penetration of frost. It thus becomes possible to reclassify the frost-sensitive soils described at the beginning in the manner shown in Table VI.

Generally speaking this enables us to recognize, and to determine quantitatively, those measurable properties of the soil and of the soil-water system which reveal direct relationships between ground frost and soil properties, and also we are able to characterize the latter with suitable measurements.

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Table I

Classification of test materials

Laboratory No.	4002	6618	7071	8699
Plastic limit	40.9	29.5	45.1	—%W
Plasticity index	24.0	7.2	16.7	—%W
Grain distribution				
Less than 2 mm	100.0	—	100.0	100.0%
Less than 0.2 mm	99.6	100.0	84.8	98.3%
Less than 0.02 mm	88.2	95.0	93.1	74.1%
Less than 0.002 mm	35.8	85.0	4.6	4.6%

Table II

Freezing tests with TiO_2 6618

Test No.	Test conditions	Measured			
	σ_3 kg/cm^2	u kg/cm^2	$\sigma_1 - \sigma_3$ kg/cm^2	Def. mm	$\Delta u + (\sigma_1 - \sigma_3)$ kg/cm^2
3	1	4.0	3.2	—	7.2
4	1	3.7	3.0	—	6.7
6	1	6.9	—	3.0	6.9
16	1	4.4	2.8	—	7.2

Table III

Freezing test with silt 8699

Test No.	Test conditions	Measured			
	σ_3 kg/cm^2	$\sigma_1 - \sigma_3$ kg/cm^2	u kg/cm^2	$\sigma_1 - \sigma_3$ kg/cm^2	Pore water forced out cm^3
9	1.0	1.0	0.72	1.0	—
10	1.0	—	0.52	0.76	—
11	6.0	—	5.70	0.73	—
12	8.0	—	7.18	1.0	—
13	1.0	—	—	—	4.3
14a	6.0	—	—	0.08	10.8
15	1.0	—	—	0.58	6.5
17	1.0	—	0.6	0.26	—
22a	2.0	—	1.45	0.53	—

Table IV

Freezing tests with clayey silt 4002

Test No.	Test conditions	Measured
	σ_3 kg/cm²	u kg/cm²
40	1	0.24
41	1	0.20
42	8	0.95
43	8	1.2

Table V

Compressive strengths of soil samples
before and after a freezing and thawing cycle

Test material	σ max. before freezing and thawing kg/cm²	σ max. after freezing and thawing kg/cm²
Clayey		
Silt 4002	0.6	0.4
Silt 8699	1.67	1.56
TiO_2 6618	4.71	2.91

Table VI

Classes of frost-sensitive soils

I	II	III
Heaving Formation of ice lenses Not frost-proof Not plastic Migration of pore water from the unfrozen strata to the frost boundary	No heaving Formation of ice lenses Not frost-proof Plastic Segregation of pore water in the freezing strata at the frost boundary	No heaving No formation of ice lenses Frost-proof Not plastic Squeezing-out of pore water from the frozen strata into the unfrozen

These materials can cause frost damage by:

I	II	III
Heaving pressure Loss of bearing strength on thawing	—— Loss of bearing strength on thawing	—— Loss of bearing strength on penetration of frost, provided the soil is sensitive to changes of water content

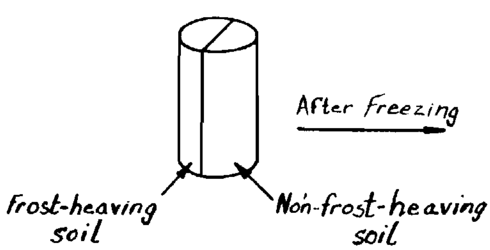

Fig. 1

Taber's freezing test

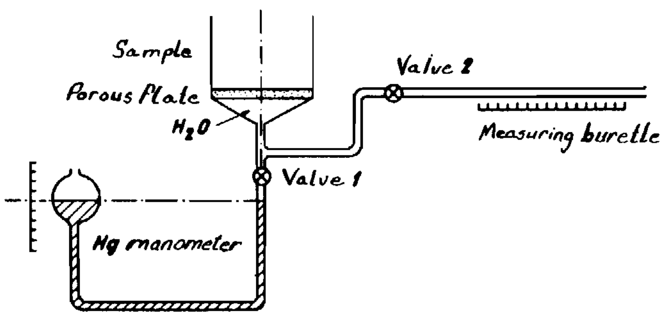

Fig. 2

Enslin apparatus

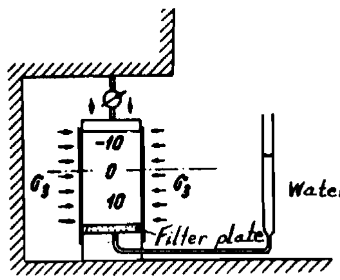

Fig. 3

Measurement of heaving pressure

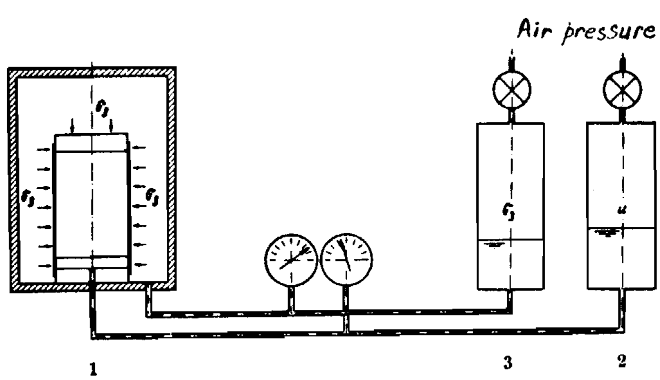

Fig. 4

Saturation of samples

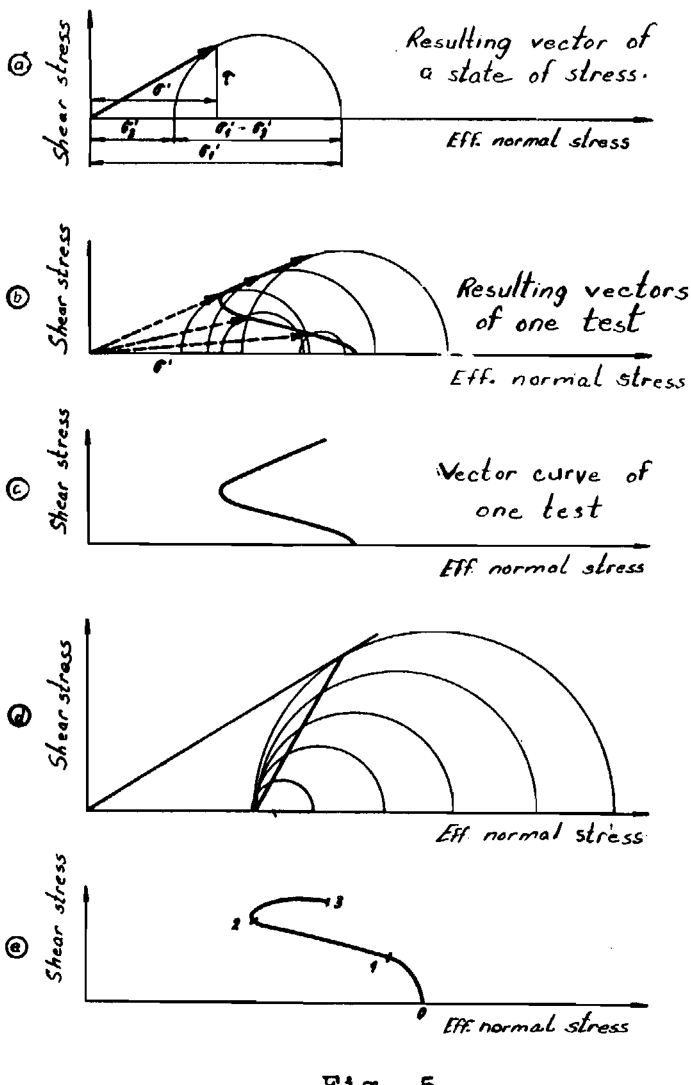

Fig. 5

Representation of the vector curve

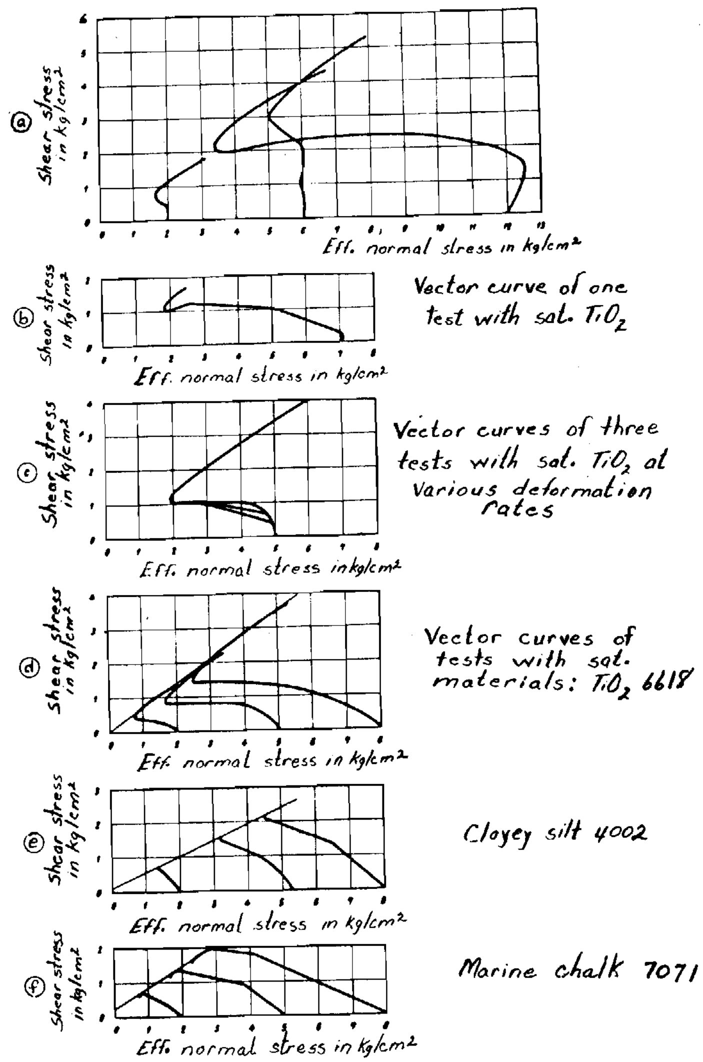

Fig. 6

Vector curves from the test with unsaturated TiO_2 6618 (a) and with the saturated materials TiO_2 6618 (b,c,d), clayey silt 4002 (e) and marine chalk 7071 (f)

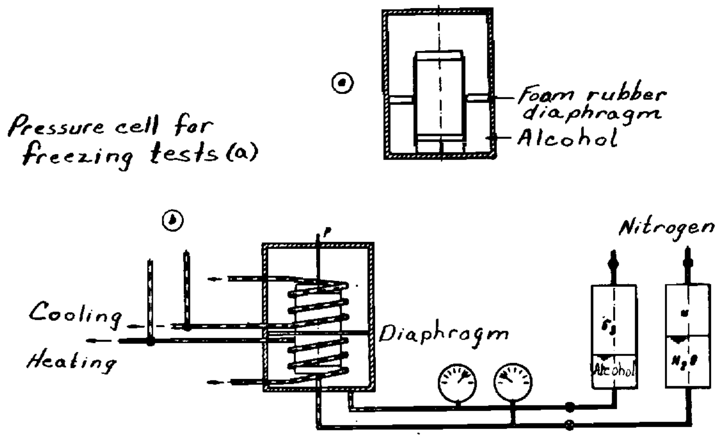

Fig. 7

Apparatus for freezing tests (b)

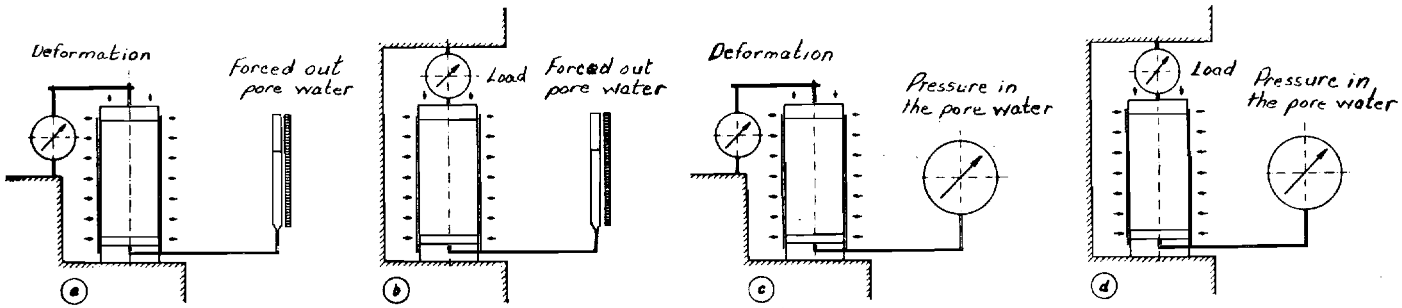

Fig. 8

Freezing tests

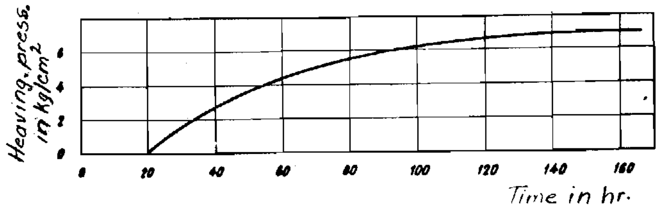

Fig. 9a

Heaving pressure of unsaturated TiO_2 6618

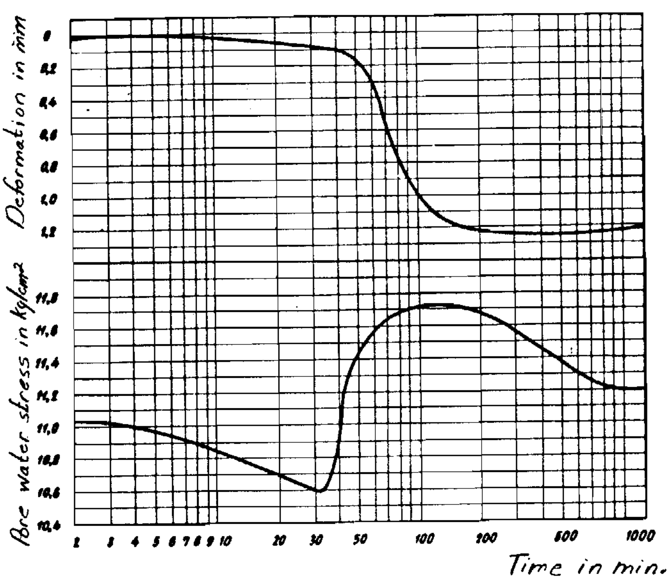

Fig. 9b

Test No. 9 with silt 8699