INVESTIGATION OF CREEP OF CLAY SOILS AT SHEAR

INVESTIGATION DE FLUAGE DES SOLS ARGILEUX EN CISAILLEMENT
ИССЛЕДОВАНИЕ ПОЛЗУЧЕСТИ ГЛИНИСТЫХ ГРУНТОВ ПРИ СДВИГЕ

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SYNOPSIS. 1.Repeated jump-like reorganization of soil structure and reorientation of clay particles occurs in process of creep at shear. No steady creep with constant rate was observed. The process consists of two phases:mobilization of shear strength and rupture.Microeffect at creep is described by equation of power function. A rheological equation is proposed where soil behaviour is characterized by static viscosity.This equation describes macroeffect at creep for the phase of mobilization. 2.The results are presented of investigation on regularities of shear creep in water-saturated clay of natural structure at +14 , +21 and +40 C under torsion. It is revealed that,depending on the level of tangential stresses,the creep deformations are of attenuating and non attenuating character. The attenuating and non-attenuating deformations are described separately by physical equations of the hereditary theory of creep. It is showed the remarkable influence of temperature over the viscosity of soil.

INTRODUCTION

The paper contains some results of the investigations of creep phenomena at shear performed in recent years in the Armenian Academy of Sciences,Yerevan. The first part is written by Prof.G.Ter-Stepanian and the second one by Prof.S.Meschian and R.Galstian,G.E.

1.ON JUMP-LIKE REORGANIZATION OF STRUCTURE OF SOILS IN PROCESS OF CREEP

The author has shown experimentally in his report presented to the First International Conference on Soil Mechanics and Foundation Engineering,held in 1936 that a jump-like reorganization of soil structure and orientation of scale-like clay particles occurs in process of shear at a certain value of tangential stresses;less durable random soil structures are replaced by orientated ones, which are more durable due to greater number of contacts between particles(Ter-Stepanian, 1936).The term "soil structure" denotes to the type and arrangement of soil particles and correspondingly,to a certain system of contacts. The greater is the number of contacts the lesser is the average stress in each of them and therefore the more durable is the given soil structure. The present investigation has for an object to study the reorganization of structure and reorientation of particles by constant value of tangential stresses,i.e. in process of creep at shear. Experiments in this direction have been started in 1964 and were performed in the beginning on remoulded clay samples. Although each of these tests taken separately has shown a jump-like reorganization of structure by reorientation of particles,the experiments in total do not allow to draw any general conclusion since they were not reproducible. Thus was proved that tests on remoulded soil samples("pastes") are in principle unusable by investigation of creep at shear.Radically other results were obtained in tests on undisturbed soil samples. Tests were made on undisturbed samples of diatomaceous clay from Upper-Miocene lacustrine deposits(Sisian district in Armenia, tunnel of Shamb hydroelectric plant,depth 40 m.). Soil is characterized by the following values: γ=1,50 g/cm^3; w=81,6%; γ_s=2,41 g/cm^3; w_L=117; w_P=58,5; e=1,94; S_r=1,0; c'=0,45 kg/cm^2; tg φ'=0,89. Tests were carried out on ring shear apparatus with external diameter of samples equal to 125 mm. and internal one -85 mm.;the height of samples - 15 mm. Fifteen tests were made in all; normal stress σ in tests was 0,5, 1,0 or 1,5 kg/cm^2,tangential stress τ varied from 0,2 to 0,55 of the normal one. The duration of tests has ranged between 150 and 500 days. A typical result of test is shown on Fig.1(σ =1,0 kg/cm^2, τ = 0,4 kg/cm^2). The test is presented by a series of curves in arithmetical scale: curve A shows the initial stage of the test (up to 90 seconds),curve B-the next stage (up to 10 minutes),etc. The corresponding scales are shown below. Ordinates for curves A-E are shown on the left side,for curves F and G - on the right one.

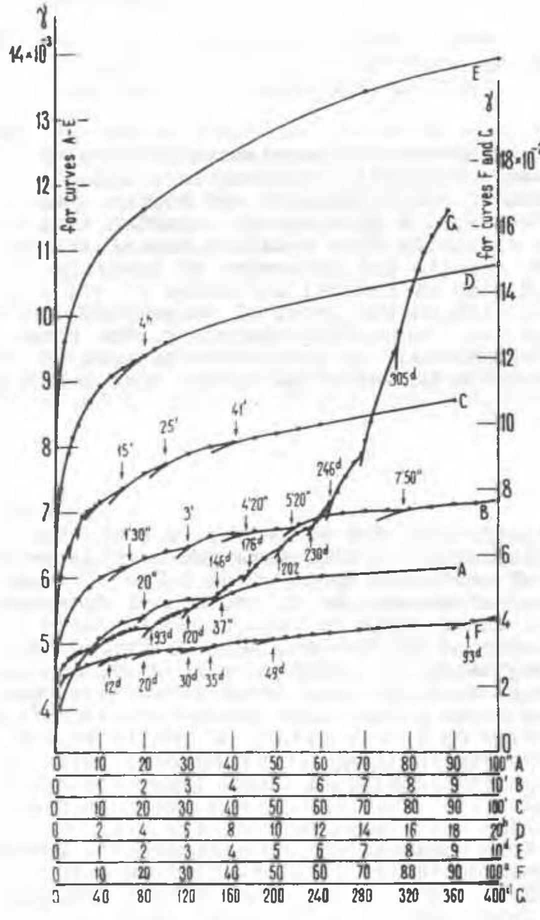

FIG.1.CREEP CURVES AT σ =1,0 kg/cm^2 AND τ= 0,4 kg/cm^2

All the performed tests have given analogous results.The graphs allow to draw the following conclusions. 1.The time-strain(creep) curves are not smooth. They consist of separate segments of smooth curves with abrupt transition from one segment to the other. Each of these smooth curves corresponds to a certain soil structure;transfer from one structure to the other is clearly seen on graphs. Each of the subsequent structures is able to undergo greater strain,i.e. it is more durable. Thus a progressive mobilization of shear strength takes place. The reorganization of soil structure occurs jump-likely; as a result more regular orientated arrangement of scale-like particles originates. 2.There are no rectilinear segments on creep curves. It seems that the final parts of almost each of these curves may be considered as a rectilinear one;however the same segment on the subsequent curve is obviously curvilinear. Hence it is concluded that the idea of the rectilinear segments (steady creep with constant rate of strain) is a result of scale effect. Rectilinear segments were never observed in our tests. 3.Experimental creep curves may be replaced by smooth curves or interpreted as such ones only if fine pecularities of the process are neglected,particularly the jump-like change of soil structures. The changing of strain rate during test was determined by graphical differentiation of the creep curves. The relationship between time and shear strain rate $\dot{\gamma}$ for test at σ=1,0 kg/cm^2 and τ=0,4 kg/cm^2 is shown on logarithmic scale on **Fig. 2.**

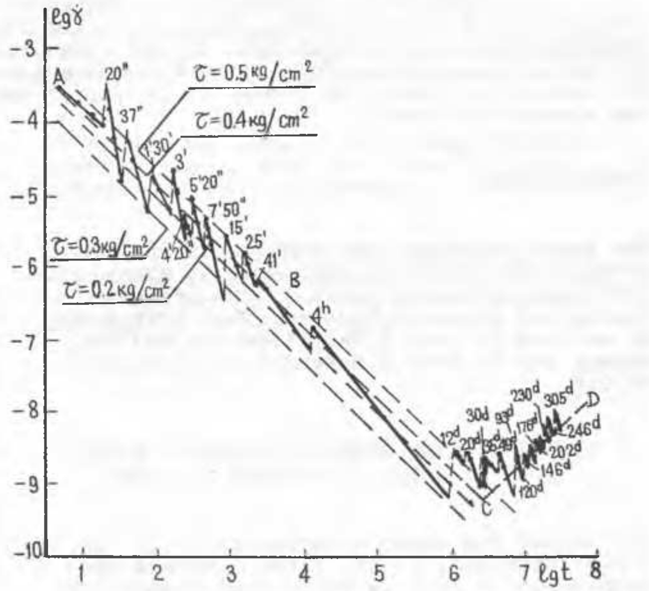

FIG.2. GRAPHS OF CREEP RATE AT σ =1 kg/cm^2
AC - PHASE OF MOBILIZATION,
CD - PHASE OF RUPTURE

In all performed tests such graphs consist of two branches AC and CD corresponding to subsequent phases of the experiment.The first phase AC is the phase of mobilization of shear strength.It may be devided into two parts AB and BC.The initial part AB consists of steep rectilinear segments connected by vertical passages.Each steep segment corresponds to the smooth creep curve of the soil structure,while vertical passages reflect the jump - like reorganization of the structure. Zone of sliding is formed during the first stage. Rupture of bonds between particles and local rearrangement of soil structure in separate lots of the soil mass takes place permanently in this phase. The reorganized zones are temporarily disloaded and forces are re-distributed on the adjacent lots. However, such small, local changes of soil strength are not reflected on strain readings because of the stiffness of rings. The process embraces avalanche - likely the whole zone of sliding in certain moments of time when the adjacent lots are overloaded sufficiently, and then well observable jumps take place. Rough surface of sliding with orientated scale-like particles is formed to the end of this stage. The final part BC of the phase of mobilization is represented by brocken line, without sharp transitions from one segment to the other. Each rectilinear segment of this line corresponds to a separate structure, too. Further formation of the sliding surface occurs in this stage, separate projection are cut off and the surface becomes smooth; several subparallel surfaces of sliding are formed sometimes. The rate of strain continues to decrease. If the tangential stress along the sliding surface does not exceed the long-term strength of the soil, the process is finished. Each of steep segments of the graph, corresponding to separate soil structures is described by equation

$$\dot{\gamma} = \dot{\gamma}_1 t^{-a} \qquad (1)$$

where $\dot{\gamma}_1$ is the strain rate of the given structure in 1 second after application of shear (if this structure had existed at that time), t-age of stresses and a-angular coefficient. Eq.(1) expresses the microeffect at creep. The process in the phase of mobilization may be represented by an averaging line AC forming an angle 45° with the coordinate axes if the logarithmic scales on them are equal. Therefore the averaging straight line for the phase of mobilization is described by equation

$$\dot{\gamma} = \dot{\gamma}_1 / t \, , \qquad (2)$$

where $\dot{\gamma}_1$ is the average strain rate in 1 second. The strain rate graph for the phase of rupture may be represented by another averaged straight line CD. Averaged lines of the phase mobilization for the other three tests at σ = 1.0 kg/cm² and τ = 0.2, 0,3 and 0,4 kg/cm² are shown on Fig.2.

Relationship between τ and $t\gamma$ for all tests at σ = 1.0 kg/cm² and for stress ages from 10 to 10⁶ seconds is shown on Fig.3. It is obvious from this curve that in coordinate system $\tau - t\gamma$ the creep test results in a wide range of time and in a great interval of tangential stress (up to 0,4 kg/cm²) are represented by a straight line forming an angle ψ with abscissas.

This line is described by equation

$$\tau = \tau_0 + \zeta t \gamma \qquad (3)$$

where t - age of tangential stress and $\zeta = \tan\psi$ is a siol characteristic which we denote as a static viscosity; it may be defined as a relation of dynamic viscosity η to the time elapsed after the application of shear stress. This equation describes macroeffect at creep in the phase of mobilization.

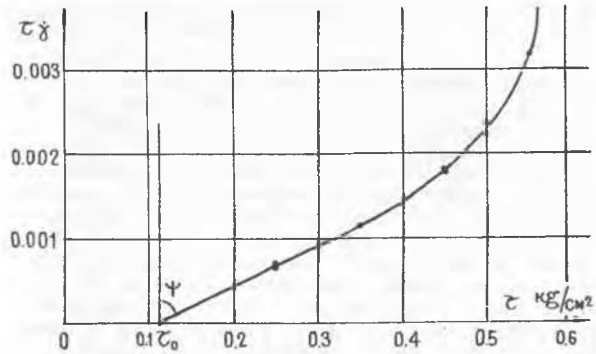

Fig. 3. Relation between shear stress τ and $t\gamma$ in the phase of mobilization irrespective of the stress age.

Static viscosity is a relation to time t of the tangential stress, which is necessary to maintain a rate difference equal to unity between two parallel layers of soil located one from another on a distance equal to unity. The dimension of the static viscosity is FL^{-2}. The static viscosity for the given normal stress is a constant value; for the soil being studied at σ = 1.0 kg/cm² it equals to 205 kg/cm² irrespective of the stress age. The dynamic viscosity of the same soil at σ = = 1.0 kg/cm² varies in such broad limits as 2.05·10³kg.sec/cm² for the stress age 10⁶sec. The dynamic viscosity for the same values of stress age makes up such broad limits as 2.22·10³and 2.04·10⁸kg.sec/cm², correspondingly. Bingham body is a reasonable model of soil in problems where the dynamic viscosity is invariable, e.g. by investigation of depth creep of natural slopes. In most cases the duration of shear stresses is comparable with the duration of the period being studied; in such cases the dynamic viscisity changes on several orders, and for such problems the model of Bingham body is unusable. In such cases the body described by equation (3) is reasonable. It is advantageous to use the conception of static viscosity as compared with dynamic viscosity by calculation of creep in the initial phases of application of shear stresses, the more so that there is no need in high accuracy; such are calculations of depth creep of exavated slopes or of retaining constructions.

The author is grateful to Senior Engineer Paitsar Terterian for exoellent experiments.

2. INVESTIGATION OF CREEP OF CLAY SOIL UNDER SHEAR, TAKING ACCOUNT OF TEMPERATURE EFFECTS

The creep of regular (nonfrozen) soil under shear, taking account of its temperature variation with time, is treated in Ref.(Meschian, 1966). The present paper is concerned with the investigation data on clay creep under shear, showing the effect of temperature on the creep regularities, the velocity of flow and the viscosity factor in its single state. To solve the problem under consideration there have been tested three series of twin-samples of tertiary clay of natural structure(γ =1,92 g/cm^3.w=26%, w_L =46,89%, w_p = =25,71%, e=0,73, S_r=0,969), taken in the vicinity of Yerevan, at σ_z =2 kg/cm^2 and at three values of temperature: T=14°, +21° and +40°C. The experiments have been carried out on torsion apparatus(Meschian, 1967). Samples of inner diameter d =101 mm, outer diameter d =50 mm, height h=24 mm have been tested for torsion. In order to ensure a uniform initial density-moisture(state) and invariability of condition of samples of all the series in the process of torsion, the latter (prior to experiment) were subjected to precompression under constant stress σ_z = =2 kg/cm^2 during 31-41 days at a temperature T=+40°C. This made it possible to acheve the most efficient compression of samples, to eliminate the effect of thermocompression and to estimate the influence of temperature on soil creep. At each prescribed temperature six pairs of watersaturated twin-samples were tested by constant relative torques M_t/M_1 =6.1;0.3;0.48;0.67 and 0.81 and by stepwise increasing relative moments(M_t is the torque; M_1 is the limit torque corresponding to the limit resistance of the soil to shear). The limit torque (M_1)was determined by testing twin-samples according to the standard technique-by the method of slow shear. The order of application of torque up to the prescribed value was similar to that for determination of M_1. The prescribed temperature of the sample was maintained by the thermostat accurate to $\pm$ 0.5°C. During the test for torsion the deformations of both compression and shear were measured. The deformations of shear were measured on the outer circumference of circular samples with the Maksimov deflectometer accurate to 0.01 mm.

In Fig.4 are shown the graphs of one of the three sets of curves for the soil creep examined. In the left sides of the graph are shown curves of dependence of shear creep relative deformation on torque and relative torque for t=50 days.

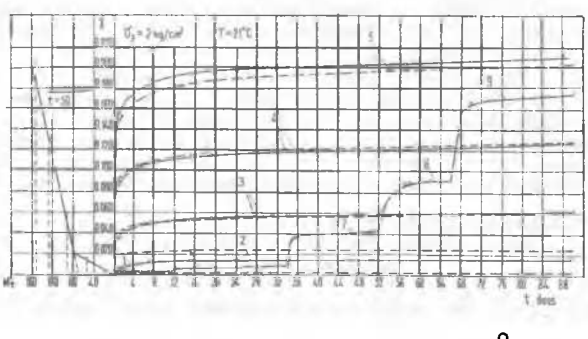

FIG.4. SETS OF CREEP CURVES AT T=21°C, σ_z =2 kg/cm^2 AND CURVE $\gamma = f_1(M_t)$. 1.M_t=18,3; 2.M_t=53,9; 3.M_t=92; 4.M_t=129; 5.M_t=155; 6.M_t = =54,9; 7.M_t=91,5; 8.M_t=128; 9.M_t=155 kg.cm

As in the earlier studies(Meschian, 1967), depending on the level of torque, the creep curves are both of attenuating ($M_t/M_1 \leqslant$ 0.3) and of nonattenuating nature ($M_t/M_1 \geqslant$ 0.5). The curves of the dependence $\gamma = f_1(M_t)$ are approximated by a broken line characterizing an elastic-plastic torsion of soil with a linear strengthening. In order to describe the sets of creep curves and to determine the soil creep parameters under shear by the torques(M_t), applied to the samples, their appropriate tangential stresses (τ) were found, operating at a distance r_2 from the circle centre(r_2 is the outer radius of the circle). Within the first length of the broken line the tangential stresses were determined from the solution of the elastic problem by the expression

$$\tau = \frac{2M_t}{\pi (r_2^4 - r_1^4)} r_2 \qquad (4)$$

where r_1 is the inner radius of the circular sample.

The tangential stresses, operating in the second region of deformation, are determined from the solution to the torsion problem of the nonlinear theory of elasticity(Kauderer, 1961):

$$\frac{dM_t}{d\gamma} + 3M_t = 2\pi \left[r_2^3 \tau(r_2) - r_1^3 \tau(r_1) \right], \qquad (5)$$

where $dM_t/d\gamma$ is the angle between torsion curve and the axis

In the case of torsion of solid sample(r_1=0) from (5) we shall obtain

$$\tau(r_2) = \frac{1}{2\pi r_2^3} \left[3M_t + \gamma \frac{dM_t}{d\gamma} \right]. \qquad (6)$$

In the first region of deformation expression (5) will assume the form of (4).

It follows from expression (5) that for determining (r_1) one should know the value of τ at r=r_1. The value of (r_1) as premier approximation, can be found from expression(4). Then from (5) taking account of (4) we shall obtain

$$\tau(r_2) = \frac{1}{2\pi r_2^3} \left[3M_t + \gamma \frac{dM_t}{d\gamma} + \frac{4M_t\, r_1^4}{r_2^4 - r_1^4} \right]. \qquad (7)$$

Taking account of the fact that in this case r_1 is small compared to r_2 and hence r_1^3 is more than ten times smaller than r_2^3, the value of $\tau(r_2)$ with the accuracy sufficient for practical purposes can be determined from expression (6) as well. The values of tangential stresses, found from expression(4), are shown in Fig.4.

In Table 1 are listed the values of tangential stresses, found from (7) and (6), corresponding to the torques, applied to the samples. Therein are also shown their values, found from expression (4) at $r_1 \neq$ 0 and r_1=0, assuming the linear dependence between the tangential stresses and relative deformations of shear. According to the data, listed in Table 1, on using expression (6), the tangential stresses, found from expression (7), decrease by 7%, while in the case of expression (4), these increase up to 15%. Since the spread of the values of tangential stresses is within the experimental accuracy, the tangential stresses $\tau(r_2)$ can with the accuracy sufficient for practical purposes be found from one of the foregoing expressions: (6), (7) or (4).

Table 1

Torque(M_t), kg.cm		92	129	155
$\tau(r_2)$, kg/cm^2 found by nonlinear theory of elasticity	by ex. (7)	0.41	0.60	0.74
	by ex. (6)	0.38	0.56	0.69
$\tau(r_2)$, kg/cm^2, found by solution of elastic problem	by ex. (4)	0.48	0.68	0.81
	dito at $r_1=0$	0.46	0.64	0.77

In order to describe the process of soil deformation with time under shear, according to Andrade, the total relative deformation of shear(γ) is expanded into two components - the attenuating deformations(γ_d) and the deformations of steady creep-flow(γ_f):

$$\gamma(t) = \gamma_d(t) + \gamma_f(t). \qquad (8)$$

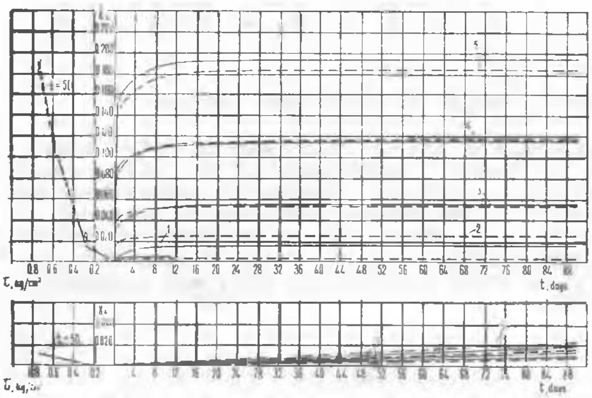

FIG.5. SETS OF CURVES FOR ATTENUATING AND NONATTENUATING SHEAR DEFORMATION AT T=21°C σ_z=2 kg/cm^2 AND CURVES $\gamma=f(\tau)$ FOR 1. τ=0,096; 2. τ=0.28; 3. τ=0,41; 4. τ=0,60; 5. τ=0,74 kg/cm^2

The graphs of sets of creep for attenuating and nonattenuating relative deformations of shear for one of the constant temperatures are shown in Figs.5. The experimental curves in the graphs are given by continuous lines. In the left sides of the same graphs are shown the curves of the tangential stress versus relative shear deformation dependence. The curves for the tangential stress versus relative velocity of flow deformation, $q=f_2(\tau)$ are shown in Fig.6. As in earlier works (Haefeli, 1953; Shakhuniants) the dependence $q=f_2(\tau)$ is a linear one and it may be approximated by the familiar equation of Shvedow-Bingham.

A comparison of the sets of creep curves, determined at various temperatures of soil, T=14°, 21° and 40°C, shows that the attenuating creep deformations differ but little from one another. The maximum discrepancy between them does not exceed 20%. This is due to the fact that all the soil samples tested had identical initial density-moisture and that is why the effect of temperature was mainly observed in the second part of the deformation-flow deformation. As will be seen below, the variation in temperature within the ranges in question doubled the change in the flow velocity.

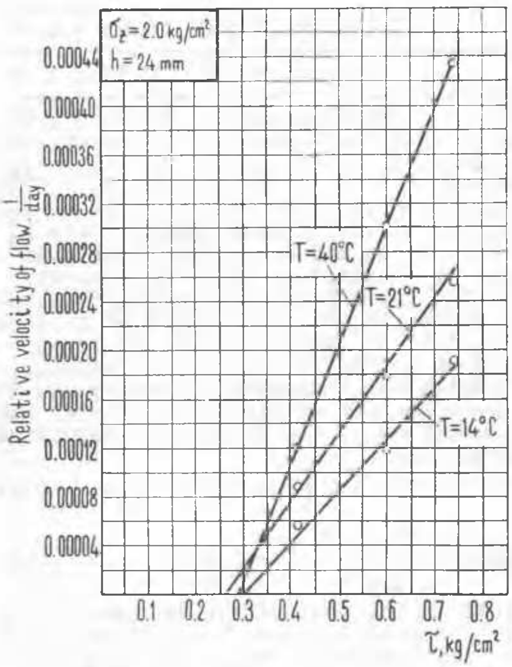

FIG.6. GRAPHS OF FUNCTIONS $q=f_2(\tau)$ AT THREE VARIOUS TEMPERATURES

The sets of curves for attenuating creep deformations are described by the expression of the form (Arutiunian, 1952):

$$\gamma_d(t) = \omega_d(t-\vartheta, T)\cdot F(\tau, T), \qquad (9)$$

where $\omega_d(t-\vartheta, T)$ is the temperature-dependent measure of attenuating creep deformation; $F(\tau, T)$ is the temperature-dependent function of stress taking account of nonlinear dependence between tangential stresses and relative deformation of shear; t is the time; ϑ is the current time coordinate (the instant of tangential stress application). The measure of creep $\omega_d(t-\vartheta, T)$, at $(t-\vartheta) \geq 1$ day, is found from the following expression:

$$\omega_d(t-\vartheta, T) = A(T)\left\{1-\exp\left[-\gamma_1(T)(t-\vartheta)\right]\right\} + \left[C(T)-A(T)\right]\left\{1-\exp\left(-\gamma_2(T)\left[(t-\vartheta)-1\right]\right)\right\} \qquad (10)$$

and the function of stress from the power dependence:

$$F(\tau, T) = \tau^{n(T)}, \qquad (11)$$

where C(T) is the temperature-dependent limiting measure of creep; A(T) is the temperature-dependent deformation at $t-\vartheta=1$ day; $\gamma_1(T)$ and $\gamma_2(T)$ are the functions determined from the experiment.

The parameters of expressions (10) and (11), found from the description of the sets of curves of creep attenuating deformations, are listed in Table 2, and the results of description of the curves in the graphs, Fig.2a, are shown by dashed lines.

Table 2

Temperature of soil(T), °C	A	C	γ_1	γ_2	n
14°	0.28	0.37	10	0,19	2.12
21°	0.28	0.34	10	0.19	2.10
40°	0.38	0.47	10	0.18	2.20
Mean value of parameters	0.31	0.39	10	0.19	2.14

The analysis of the data, listed in Table 2, shows that γ_1, γ_2 and n are practically independent of temperature with the accuracy sufficient for practical purposes(±15%)A and C may also be assumed independent of temperature. The sets of curves for steady creep (flow), shown in Fig.5b with linear dependence between the tangential stresses and relative deformations of flow in a general case may be described by the following expression (Meschian, 1967):

$$\gamma_f(t)=q(T)(t-\vartheta)\left[\tau-\tau_o(T)\right] \quad (12)$$

$$\gamma_f(t)=\frac{\tau-\tau_o(T)}{\eta(T)}(t-\vartheta), \quad (13)$$

where q(T) is the temperature-dependent relative velocity of flow at $\tau-\tau_o(T)=1$; $\tau_o(T)$ is the temperature-dependent limiting stress of shear (creep threshold by N.N.Maslov, 1958); $\eta(T)$ is the temperature-dependent viscosity factor $\left[\eta(T)=\frac{1}{q(T)}\right]$.
The values of a relative flow velocity(q) and of a limiting stress of shear(τ_o), determined by the description of sets of curves for steady creep(Fig.5) are listed in Table 3. The same Table contains the values of the viscosity factor(η), determined for three different values of temperature.

Table 3

T°C	q, $\frac{1}{day}$	τ_o, kg/cm²	η	
			$\frac{kg}{cm^2}$day	Poise
14	0.000441	0.3	2268	$1.96\cdot10^{14}$
21	0.000550	0.26	1818	$1.57\cdot10^{14}$
40	0.000963	0.28	1038	$0.9\cdot10^{14}$

The data listed in Table 3, show that the relative velocity of creep and the viscosity factor strongly depend on temperature. With temperature change within +14°C to +40°C these values change nearly 2.2 times. At the same time under constant soil density-moisture in the process of shear, with accuracy sufficient for practical purposes(±7%), may be assumed independent of temperature.

Then expression (9) may be represented in the form:

$$\gamma(t)=\omega_d(t-\vartheta)\tau^n+q(T)(t-\vartheta)(\tau-\tau_o) \quad (14)$$

or

$$\gamma(t)=\omega_d(t-\vartheta)\tau^n+\frac{\tau-\tau_o}{\eta(T)}(t-\vartheta). \quad (15)$$

In the graph of Fig.4, by way of example, the dashed lines show the results of description of the sets of creep curves by expressions (14) and (15).
The graphs of curve for the dependence $q=f_3(T)$ is shown in Fig.7.

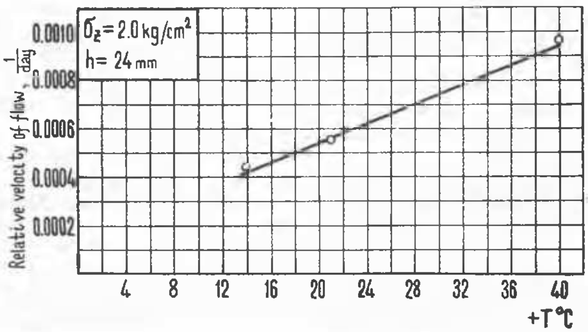

FIG.7. GRAPH OF FUNCTIONS $q=f_3(T)$

Summarizing the above, it may be noted, that in the case of steadiness of the soil density-moisture in the process of shape-changing (torsion) the temperature effect on creep can be taken into account by means of the temperature functions of the relative velocity of flow deformation q(T) and viscosity η(T).

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