Correlation between the Frost Heave and Granulometry of Soils

La Corrélation entre le gonflement dû au gel et la granulométrie des sols

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SUMMARY

Previous studies state that the frost heave of soils is due to their grain size distribution. In this study the author shows that the rate of frost heave is a function of the maximal grain size of the soil (D_0), its surface area (ϕ), and chemical properties (ch). The author gives a mathematical formula in terms of minutes × C°, which is proportional to the rate of heat extraction:

$$\xi = \Upsilon(\mathrm{ch})/\Psi(\phi)[f(D_0) - \Upsilon(\mathrm{ch})] + \Psi(\phi)[f(D_0) - \Upsilon(\mathrm{ch})](\textstyle\sum \Delta t \Delta C^\circ)$$

The author demonstrates further that, given certain physical characteristics, the extent of frost heave can be computed from liquid limit data.

SOMMAIRE

Au cours de toutes les études on a constaté que le gonflement des sols dû au gel est occasionné par la granulométrie. Dans son étude l'auteur démontre que la vitesse du gonflement dû au gel est en fonction de la dimension maximale des granules du sol (D_0), de sa superficie (ϕ) et de ses propriétés chimiques (ch). L'auteur présente une formule mathématique en fonction de minutes × C°, qui est proportionnelle à la vitesse de l'extraction de chaleur:

$$\xi = \Upsilon(\mathrm{ch})/\Psi(\phi)[f(D_0) - \Upsilon(\mathrm{ch})] + \Psi(\phi)[f(D_0) - \Upsilon(\mathrm{ch})](\textstyle\sum \Delta t \Delta C^\circ)$$

De plus l'auteur démontre que certaines caractéristiques concernant l'état du sol étant données on peut calculer le gonflement dû au gel, en utilisant les données de la limite de liquidité.

THE PHYSICAL CHARACTERISTICS OF SOILS seem to be strictly and unambiguously correlated with the grain size distribution. The correlation between the granulometry and liquid limit or permeability of soils has been described previously (Járay, 1958, 1959, 1961).

FUNDAMENTAL IDEA OF THE EXPERIMENT

It was made clear by earlier experiments that the frost danger was connected, in conformity with certain rules, with the grain size distribution (Beskow, 1932, 1947; Clare, 1948; Dücker, 1939; Erlenbach). The higher the clay content of the soil to be investigated, the more serious will be the developing frost damage (Buisson, 1942; Casagrande, 1936; and Jáky, 1936, 1939). These were the practical data which furnished the fundamental idea of the present experiment: that is, the amount of the frost heave could be expressed in terms of the grain aggregation characteristics, maximum grain size (D_0), and surface of soil particles (ϕ).

During experiments one must imitate nature, and this demand can be satisfied by the choice of instruments to be used (Fig. 1). The causes of freezing could not be eliminated. Consequently, the experiments had to be conducted under conditions corresponding to the earth work (Bendel, 1944; Kézdy, 1962; Széchy, 1952; Ruckli, 1950; Zunker, 1930). Accordingly, the soil samples should be prepared at optimum moisture content and under intensive compaction, and the experiment should be carried out at a nearly constant temperature. In the course of the experiments only the qualitative characteristics of the material cause an essential change.

The selection of suitable soils makes possible the separate investigation of the grain size distribution characteristics D_0 and ϕ, as well as the chemical property (ch). In the experiments undertaken, six soils (sand, silt, and clay types)

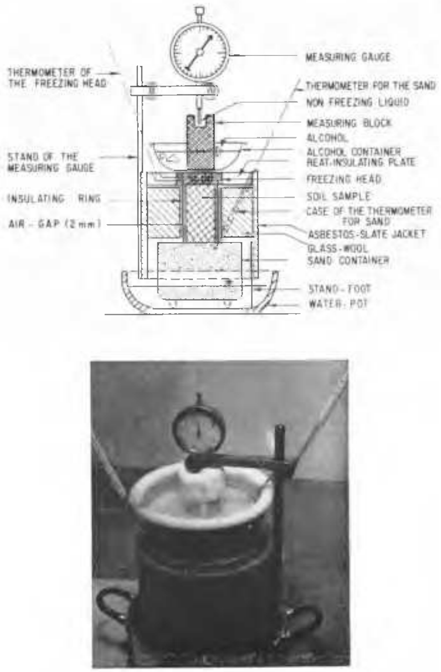


FIG. 1. Freezing device.

TABLE I. INFLUENCE OF CHEMICAL PROPERTIES ON FROST HEAVE OF SOILS

	Chemical data			Liquid limit experiments			Freezing experiments			
Symbol	Treatment	CO_3 content per cent	pH	A_F	N_F	$\frac{A_{Fe}}{N_{Fo}}$	A_f	N_f	$\frac{A_{fo}}{N_{fo}}$	Frost heave per cent
I/1	HCl	32.9	7.2	3.3	0.078		1.7	0.6		1.0
2	$MgSO_4$	37.6	7.2	3.4	0.075		0.3	5.6		> 9.0
3	$NaHCO_3$	38.8	8.9	2.9	0.092		1.4	1.7		> 1.9
4	NaOH	37.6	8.9	3.6	0.078	8.0	0.2	5.6	2.2	> 5.1
5	$KHCO_3$	37.8	8.9	3.9	0.078	0.0165	0.2	5.8	3.0	> 7.3
6	$CaCl_2$	37.0	8.4	5.9	0.044		0.8	4.1		> 3.6
7	Na_2SO_4	37.9	8.6	5.2	0.052		1.0	2.9		> 3.3
or	Original	38.0	8.2	4.3	0.060		0.1	5.8		5.9
II/1	Original	4.5	7.9	4.1	0.048		1.0	4.2		4.8
2	HCl	2.5	6.8	3.6	0.054		2.7	2.2		1.5
3	$MgSO_4$	5.8	6.6	4.0	0.048		2.3	2.7		2.6
4	Na_2SO_4	4.7	7.5	4.0	0.046	6.6	2.6	2.2	4.0	> 1.7
5	NaOH	5.1	9.5	3.9	0.048	0.0184	3.2	1.2	1.4	> 1.5
6	$CaCl_2$	3.9	7.7	3.9	0.050		3.2	1.1		0.6
7	$CaCl_2$	5.7	7.4	3.2	0.060		3.8	0.4		> 0.4
III/1	NaOH	7.3	8.4				0.2	2.0		0.7
2	$MgSO_4$	4.8	4.3				0.2	2.0		0.7
3	Na_2SO_4	4.4	7.8				1.0	1.0	1.8	1.0
4	$CaCl_2$	5.2	7.5				1.0	1.1	1.7	1.5
5	$CaCl_2$	6.8	7.2				0.6	1.5		1.5
6	Original	9.0	7.8				—	—		2.7
7	HCl	4.4	6.5				0.6	1.7		—
IV/1	HCl	1.5	6.3	2.9	0.094		—	—		—
2	Na_2SO_4	4.2	7.7	2.8	0.100		0.9	2.3		2.1
3	NaOH	5.8	9.8	4.7	0.053	7.0	0.8	2.6	1.6	2.4
4	$MgSO_4$	4.0	7.5	2.6	0.110	0.0300	0.6	3.4	4.1	3.1
5	$CaCl_2$	2.1	8.2	2.7	0.100		1.3	0.8		1.2
6	KNO_3	5.4	7.0	3.5	0.090		0.5	3.7		3.0
7	Original	2.5	8.1	4.0	0.063		0.2	5.7		6.4
V/1	Original	5.6	8.0	3.1	0.190		0.1	3.0		> 3.6
2	Na_2SO_4	4.5	7.5	4.2	0.140		0.6	1.0		> 1.3
3	$MgSO_4$	5.5	7.3	3.2	0.180	6.8	0.4	1.6	0.9	> 2.1
4	$CaCl_2$	4.2	7.4	3.2	0.180	0.0530	—	—	4.2	—
5	NaOH	5.4	9.3	3.4	0.175		0.6	1.0		1.3
6	KNO_3	4.4	7.3	3.2	0.180		0.2	2.5		0.5
7	HCL	1.3	6.3	3.6	0.200		0.5	1.2		0.5
VI/1	Original			3.5	0.140		0.8	0.7		> 2.0
2	$MgCl_2$			3.8	0.125		1.0	0.3		0.6
3	Na_2SO_4			4.2	0.120	7.0	0.8	1.0	1.0	> 2.0
4	NaOH			2.9	0.160	0.0420	0.6	1.6	3.0	> 4.0
				3.7	0.150		0.5	2.0		> 3.5

and 5 to 7 artificially produced soils were analyzed in order to define the influence exerted by the variables D_0, ϕ. Consequently, 40 chemical variants were observed, to determine the effect of the chemical variable of the soil (ch).

The grain size distributions of the investigated soils are plotted in a special co-ordinate system, elaborated by Jáky (Fig. 2). (Járay, 1958, 1959, 1961.)

EVALUATION OF RESULTS

In the course of the experiments the temperature of the freezing head, of the bedding of sand applied under the soil sample, and of the water were measured every hour and the frost heave was established as a function of time (t).

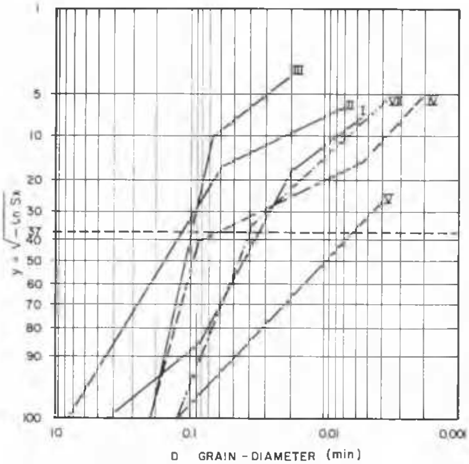
The established frost heave data were plotted as a function of the heat quantity, given by the formula $Q = \lambda(F/d)$ $(\Sigma\Delta t\Delta C°)$ where F is the surface of the cross-section of the soil sample, and d its height. Direct measurement of the heat loss (Q) is impossible, therefore for its evaluation the value $\Sigma\Delta t\Delta C°$ was used. This was due to the nearly same value of the heat conductivity possible.

Plotting the frost heave as a function of $\Sigma\Delta t\Delta C°$ the existence of straight-line relationships can be established.

1. These relationships agree with the measured results within an accuracy of $\pm$ 5 per cent. The amount of the frost heave is given by the formula (Fig. 3)

$$\xi = (A_f/N_f + N_f(\Sigma\Delta t\Delta C°). \quad (1)$$

The section of the straight line (A_f) of frost denotes the temperature needed to cool the water content of the soil to the freezing point. However, salts present in the soil and dissolved in the groundwater exert an influence not only on the freezing point of the water, but also on the chemical properties of the soil. Consequently it follows, that a definite correlation between the section A_f and the chemical property of the soil (ch) exists. According to the relation $A_f = T$ (ch), the index N_f expresses the amount of the developing ice-lens.



SYMBOL	TYPE	D_0	D_{01}	D_{02}	P	P_1	P_2	n	b	a	ϕ cm²/gr
I	A.		045	C10		2.60	1.04	1.80	0.40	060	1,050
II	C.		070	070		1.50	2.75	0.50	1.56		470
III	C.		032	032		0.86	1.76	0.30	2.00		230
IV	B.		SAMPLE FROM SOILS OF THE CATEGORIES II RESPECT. V					0.50			2,600
V	T.	015									7,300
VI	C.		014	014		1.10	3.05	0.45	2.77		2,580

FIG. 2. Grain size distribution data.

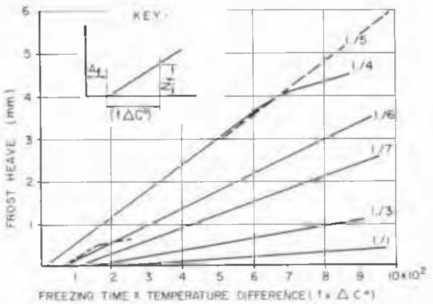


FIG. 3. Correlation between the frost heave and temperature.

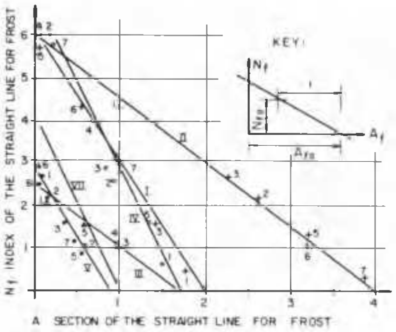


FIG. 4. Correlation straight line of soil freezing characteristics.

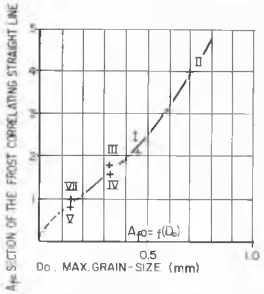


FIG. 5. Correlation between the maximal grain size and the section of the correlation straight line.

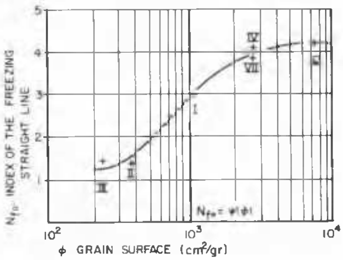


FIG. 6. Correlation between the grain surface and the index of the correlating straight line.

2. When plotting the values A_f and N_f in a co-ordinate system, the characteristic points for the various sorts of the same soil lie on a correlating straight line, thus giving the constant values A_{f_0}, N_{f_0} which are characteristic both for the investigated soil and the whole complex of variations (Fig. 4). The formula of the correlating straight line is

$$N_f = N_{fo}\,(A_{fo} - A_f). \qquad (2)$$

3. In conformity with the results supplied by the investigations on liquid limit, water permeability, and unconfined compression, the constants A_{f_0} and N_{f_0} of the correlating straight line, if the same soil is dealt with, are correlated with the grain size distribution characteristics D_0 and ϕ. The correlation between D_0 and A_{f_0} is shown in Fig. 5 while the correlation between ϕ and N_{f_0} is illustrated in Fig. 6.

4. According to formulas (1) and (2) the frost heave is

$$\xi_i = \frac{\Upsilon(\mathrm{ch})}{\Psi(\phi)[f(D_0) - \Upsilon(\mathrm{ch})]} + \Psi(\phi)[f(D_0) - \Upsilon(\mathrm{ch})](\textstyle\sum \Delta t \Delta C^\circ) \qquad (3)$$

which can be simplified to:

$$\xi = A + B(\textstyle\sum \Delta t \Delta C^\circ)$$

where the constants A and B are:

$$A = \frac{\Upsilon(\mathrm{ch})}{\Psi(\phi)[f(D_0) - \Upsilon(\mathrm{ch})]},$$

and

$$B = \Psi(\phi)[f(D_0) - \Upsilon(\mathrm{ch})].$$

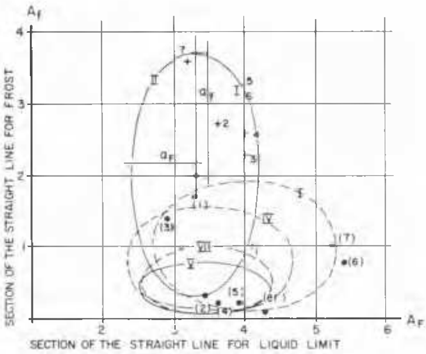
In the case of variable chemical properties (ch), provided the heat loss Q is constant, the frost heave will vary according to an equilateral orthogonally axial hyperbolic function. Thus the correlation between the grain size distribution and the frost heave of the soils is proven.

CORRELATION BETWEEN THE FROST HEAVE OF SOILS AND THE CHARACTERISTICS OF LIQUID LIMITS

The basis for investigation of this correlation was supplied by the following experimental results.

1. The section of the liquid limit straight line as well as the section of the frost straight line depend on the chemical properties of the soil. From this dependence the existence of a correlation between the two sections necessarily follows.
2. The constants of these correlating straight lines of both physical characteristics can be expressed by the grain size distribution characteristics of the soil. Thus the value of A_{FO}, A_{fo} can be expressed by the maximal grain size of the soil (D_0) and the value of N_{FO}, N_{fo} by the surface of the soil particles (ϕ). As D_0 and ϕ are parameters of both functions, the two variables are also functions of each other. This correlation is illustrated in Fig. 7. Plotting the values of A_F and A_f in a co-ordinate system, a closed function, similar to an ellipse, is obtained (Fig. 8). The elliptical form of the function is motivated by two considerations. (1) On the correlating straight line of both soil mechanics characteristics the points of chemical variations are situated on the active section, i.e., they are confined. From this it follows that in the direction of both axes of the co-ordinate system the function is confined within certain limits. (2) The base-exchange taking place on the surface of the soil particles and the variations of the sections are in correlation with each other. This correlation is a continuous one. As a consequence of this, continuous correlation must exist between the two sections, A_F, A_f. The active section is symmetrically situated on the correlating straight line. Thus the co-ordinates of the centre of the ellipse are $A_{FO/2}$, $A_{fo/2}$.

Based on the results of our experiments and by graphic determination of the semi-axes of the ellipse, which characterize the size types of soil, the correlation with the maximal grain size is fixed in Fig. 9.



SYMBOL	D_o	a_F	a_f
I	045	1.4	0.9
II	070	0.9	1.7
IV	032	1.2	0.7
V	015	0.9	0.45
VII	015	0.9	0.5

FIG. 8. Correlation between the sections of the straight lines belonging to the frost and the liquid limit.

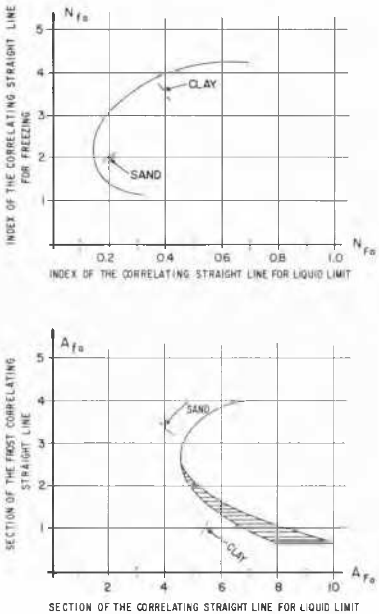


FIG. 7. Correlation between the liquid limit and the frost properties of soils.

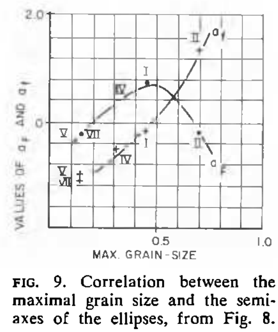


FIG. 9. Correlation between the maximal grain size and the semi-axes of the ellipses, from Fig. 8.

Thus the value of the section A_f can be determined. Consequently, the frost heave (ξ) can be computed from the data related to the grain size distribution; furthermore, a correlation between the frost heave and the liquid limit exists. The results so far obtained do not supply unambiguous data, because it follows from the elliptical correlation that to each value A_F two values A_f belong.

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