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Thixotropic Properties of Suspensions of Soils with different Grain Sizes and of various mineralogical Types

Propriétés thixotropiques des suspensions de sols de compositions minéralogiques et granulométriques différentes

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Summary

The authors present the results of research on thixotropy of suspensions of soils with different grain sizes and of various types. Some rheological problems are also discussed, particularly the relationships between Bingham limits, time of stiffening, characteristics of the soils and their concentration in suspensions.

Sommaire

Les auteurs présentent les résultats de recherches sur la thixotropie des suspensions de sols de granulomètries différentes et de divers types minéralogiques. On discute aussi de certains problèmes rhéologiques, en particulier des relations existant entre les valeurs du seuil de Bingham, le temps de durcissement, les propriétés des sols et la concentration des suspensions.

The phenomenon of reversible, isothermal changes of state "stiff — liquid — stiff", i.e. the phenomenon of thixotropy, is a particularly interesting problem of soil mechanics, where soils are able to flow and move. This consideration prompted in recent years the Institute of Building Technics to carry out investigations on thixotropy of soil suspensions and pastes as a preliminary step to the study of soil rheology. The said investigations have also facilitated a study of the technology of activated thixotropic suspensions (Piaskowski, 1956), which are of practical use in some problems of foundation engineering.

Thixotropic properties of the suspensions investigated were established from changes in one of the parameters of Bingham's body after a certain period ("stiffening time") of regeneration of thixotropic gel structures, i.e. a three — dimensional network of soil particles. The equation representing the state is of the following form :

$$v = \frac{1}{\eta}(\tau - \tau_0) \qquad (1)$$

where :

v = rate of strain,
η = viscosity,
τ = stress,
τ_0 = yield value of τ (Bingham limit).

At τ values greater than τ_0 visco-plastic flow of suspensions appears and increase of τ_0 with time of stiffening presents the most distinct feature of the phenomenon of thixotropy.

In studying various suspensions by means of Hoeppler's "Rheo-Viscosimeter" diagrams were obtained similar to those of F. Hoeppler (1952), an exemple of which is shown in Fig. 1.

The results of the studies show that deviations from equation (1) often occur at very low rates of deformation. Consequently the values of τ_s appearing in static studies ($v \approx 0$) may be lower than τ_0 (Fig. 1).

Meanwhile, for simple estimating of thixotropic properties of suspensions the usual rheological tests are too complicated and for this reason a much simpler "inverted test-tube method" was applied; this method has been described by H. Winkler (1938), E. Ackermann (1948) and others. In this method the measuring standard for thixotropic properties is the moisture content of the thoroughly stirred suspension at which, after a defined stiffening time, the suspension reaching sufficiently large τ_s value, no longer flows under its own weight from the test-tube turned upside down. The moisture content may be called "stiffness limit" — L_s and may be comparable with the Atterberg limits of consistency (Ackermann, 1948). It is determined by graphic interpolation (Fig. 2) after

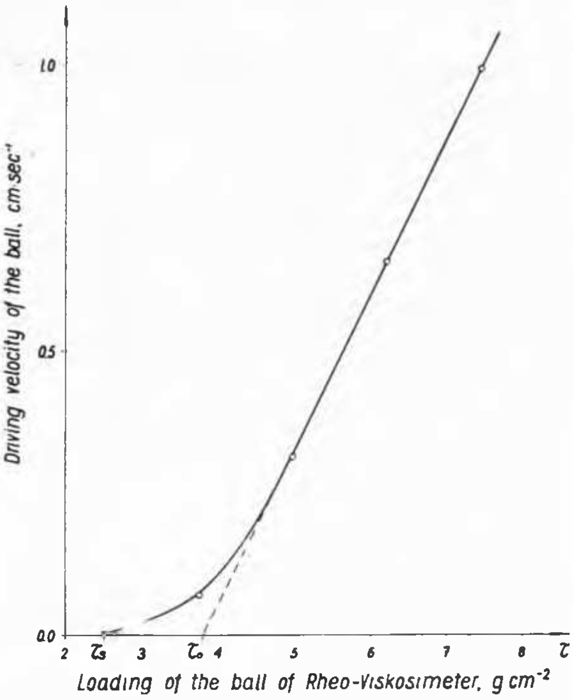

Fig. 1

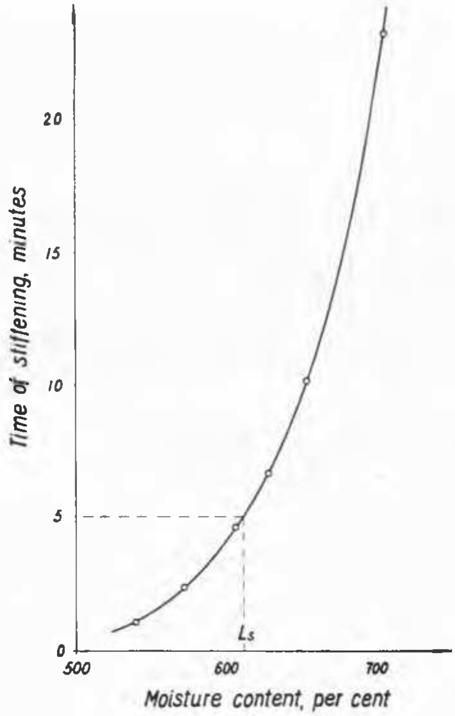

Fig. 2

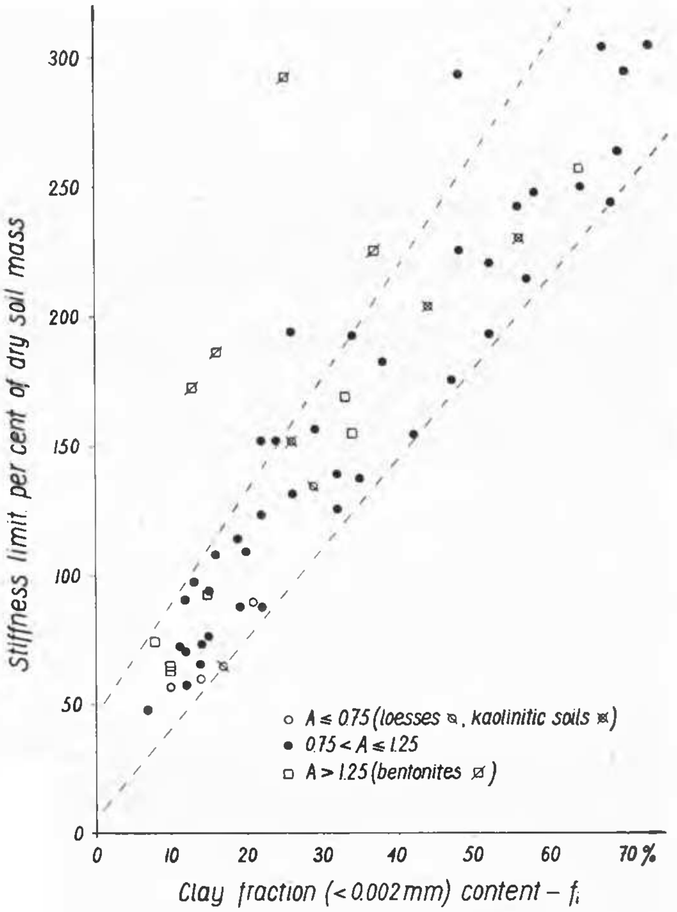

Fig. 3

several determinations of the relationship "moisture content of the given suspension-stiffening time". In this method, the inner diameter of the test-tube and the time of stiffening are essential. It was determined by experiments (PIASKOWSKI, 1956) that reasonable accuracy is achieved by applying 15 mm tubes and 5 minutes of stiffening time. In the litterature, however, other values are mentioned as well, e.g. 8 mm and one minute. It was found that the L_s values obtained when using either of these variants show a ratio which increases slightly with the L_s value (15 mm, 5 minutes), from 1·17 at L_s = 110 per cent to 1·36 at L_s = 650 per cent. Generally, the smaller test-tube diameter or the longer stiffening time, the higher L_s values are obtained.

On the basis of the L_s value determined for a given suspension, the ratio : "volume of water to volume of soil particles" — S_t, suggested by H. WINKLER (1938), can be evaluated by means of the simple formula :

$$S_t = 0{\cdot}01 \cdot G_s \cdot L_s \qquad (2)$$

where : G_s — relative specific gravity for a given soil, L_s — stiffness limit for its suspension in percentage by weight.

The average mean error has been found for the above method as ± 2·9 relative per cent.

To find the relationship between thixotropic properties of suspensions and grain-size distribution of soils and mineralogical character of their clay fraction, L_s values for 60 various soils, with 7 — 73 per cent clay fraction ($< 2\mu$) content, were determined. Soils with organic matter or lime content ($>$ 3 per cent) were not dealt with in the above investigations. The results are presented in Fig. 3 as function of clay fraction content — f_i, and in Fig. 4 (39 soils only) as function of base exchange capacity — p_w. "A" is the colloidal activity according to A. W. SKEMPTON (1953).

These diagrams permit to draw the following conclusions :

1. Fig. 3 shows that L_s values observed for kaolinitic soils and for loesses are not different from those for average (illitic) soils; but they are much higher for montmorillonitic soils (bentonites); this fact may be explained either by a specific particle shape or by greater surface activity (higher exchange capacity).

The relationship between the values of L_s and grain-size distribution of soils confirms to a large extent the conclusions presented by E. ACKERMANN (1948) and V. ROMANOVSKY (1948).

2. The relation in Fig. 4, $L_s = F(p_w)$, on the other hand, shows that in the case of kaolinitic soils and loesses (low exchange capacity) L_s is not proportional to the mean density of exchange cations on the surface of soil particles; in this case a more pronounced density of cations (to a large extent, of electrical charges) on particle edges and corners may be probably the decisive factor, that the L_s values for both these soil types are higher than for corresponding average soils with the same p_w values. This is confirmed in the case of montmorillonitic soils with a high exchange capacity, where a reverse phenomenon occurs (L_s values lower than for average soils), possibly due to a more uniform distribution of cations over the whole surface (and volume) of particles.

The above interpretation of these relationships does not take into consideration the influence of electro-kinetic potential but it may serve as a basis for the assumption that thixotropic properties of soil suspensions are influenced, to a great extent, by particle shape and the distribution of attractive forces forming mutual contacts over particle surface.

A similar conclusion can be drawn from rheological investigations, which were carried out and published in 1956 (PIASKOWSKI, 1956), and partly will be published additionally. In these investigations the following empirical relation was

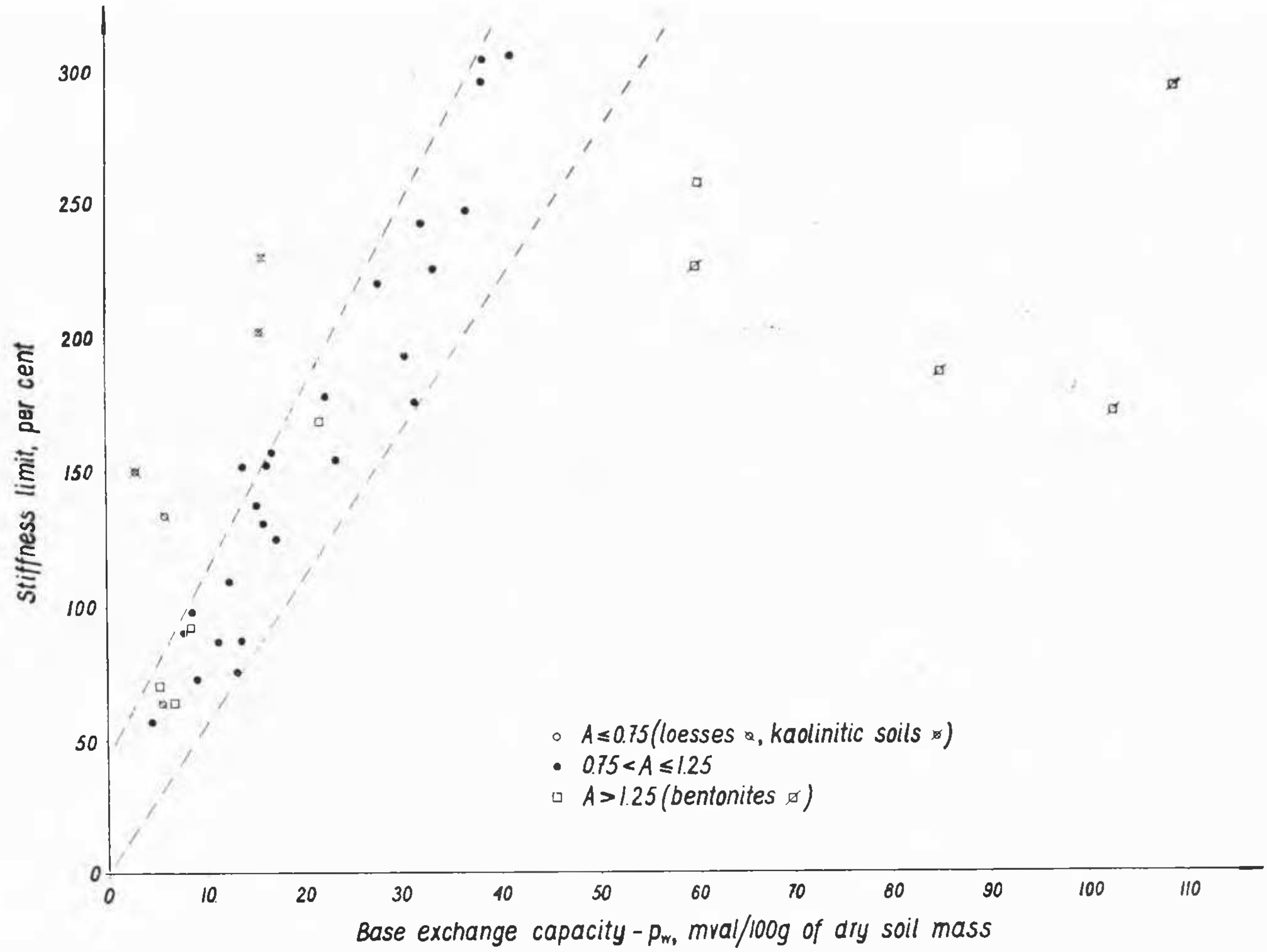

Fig. 4

determined between τ_s and soil concentration in the suspensions and time of stiffening :

$$\tau_s = k_1 e^{k_2 c_v}, \text{ where } c_v = \frac{100}{100 + w \cdot G_s} \quad \ldots. \quad (3a, b)$$

where :

k_1 = empirical coefficient increasing (probably logarithmically) as the time of stiffening increases and depending on the characteristics of the given soil,

k_2 = empirical coefficient diminishing with time and depending on the characteristics of the given soil,

c_v = volume concentration of the soil in the suspension, in per cent,

w = moisture content of the suspension, per cent by weight.

Examples of the above relationship are given in Figs. 5 and 6. It is obvious that the relative increase of τ_s in time, from 0·1 to 5·1 minutes for these two different clays is not the same. For the bentonite (Fig. 5) it grows with the moisture content of suspensions ; this may be due to a higher degree of freedom of particles in a suspension of lower concentration and to alteration of types of bonds between particles, probably ; in the case of flat particles of montmorillonite it may be particularly marked. In the case of illitic clay (Fig. 6) it is interesting to note, this phenomenon did not occur in any noticeable degree. If we assume the dependence of ratio : τ_s for the stiffening time of 5·1 minutes to the τ_s for 0·1 mi-

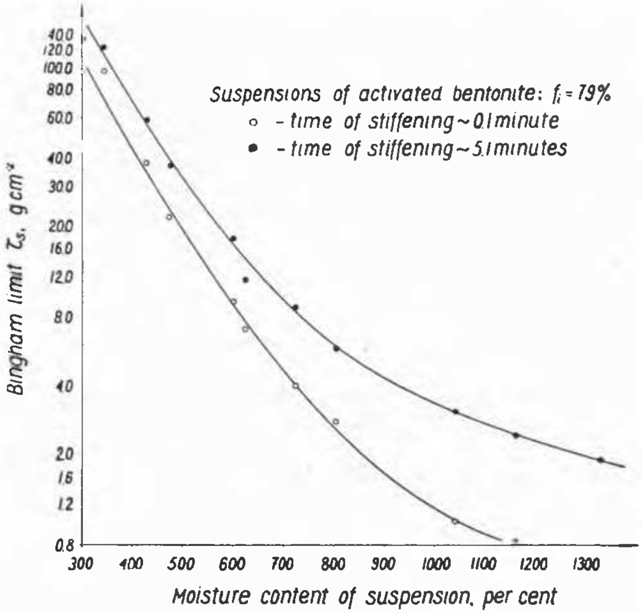

Fig. 5

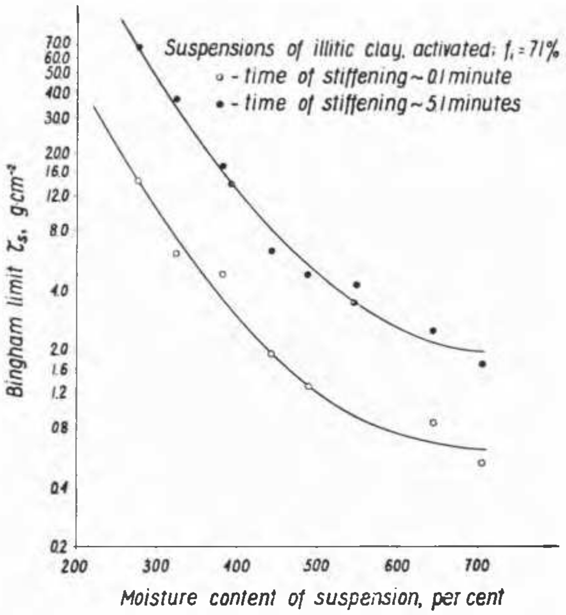

Fig. 6

nutes, on the moisture content of suspensions, we obtain the following data :

1. Activated bentonite (commercial product) — for moisture contents from 300 to 1 160 per cent the above ratio increases from 1·3-1·4 to about 3·0-3·1, what is shown in Fig. 5.

2. Illitic clay with small content of montmorillonite, activated by suitable additions of chemicals — for moisture contents from 320 to 700 per cent, the above ratio was practically constant varying within the limits 2·5 — 3·2 only. It is interesting that at low moisture contents this ratio for this clay is greater than for the above bentonite.

The above results may be explained on the basis of the network hipothesis of Tan Tjong Kie (1957), probably as follows :

(a) In case of bentonites at low moisture contents the weak particle-bonds "flat surface to flat surface" predominante, while at high moisture contents probably the stronger bonds "corner to flat surface" appear.

(b) In case of kaolinitic and illitic soils, however, bonds of the second type (and "edge to flat surface") predominante practically at all moisture contents of investigated suspensions.

The above explanation is only a hypothesis, its essence is the possibility of determining the character of particle bonds, on the basis of an analysis of Bingham limits changes depending on concentrations and characteristics of clay and on the time of stiffening.

With regard to the above investigations it should be pointed out that only the determination of the character of the above relationship is of some real value, the numerical values of τ_s depending chiefly on the various conditions, in this case mainly on the diameter of "Rheo-Viscosimeter" tube. Thus, for example, for the suspensions with concentrations of 11 — 12 per cent by weight, the τ_s values obtained with tube diameters 16·50 mm, 17·40 mm and 20·23 mm (the diameter of the ball being constant and equal to 15·96 mm) showed the ratios: 2·34 : 1·00 : 0·78, respectively.

In addition it should be pointed out that stiffness limits obtained for soils previously dried (at + 105° C) were generally somewhat lower (the correspondings ratios being 0·66 — 1·00) than for corresponding soils not being dried. As ascertained it was caused by the formation of irreversible aggregates of fine soil particles during the process of drying, i.e., by the change of the grain-size distribution of soils.

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