Flexible Pavement Design

Calculs des Revêtements Flexibles

by N. N. Ivanov, Professor Doctor, A. K. Birulya, Professor Doctor, V. F. Babkov, Professor Doctor and N. A. Puzakov, Bachelor of Science, The Highway Research Institute, The Automobile and Highway Technical Institutes of Moscow and Kharkov, U.S.S.R.

Summary

Stress distribution in the multilayer road structure has been adopted in conformity with different degrees of rigidity (characterized by the modulus of deformation) of various courses and the subsoil; the fact that the materials forming the pavement are very far from being ideal elastic materials must be taken into account.

The bearing capacity of the road structure depends upon a definite ultimate value of vertical displacement of the pavement, increasing during the wet period of the year from the repeated action of dual-tyre wheel loads of trucks and buses.

Two-stage computation is applied: the required equivalent modulus of deformation of a road structure as a whole is first determined; the thickness of various courses is then derived according to the given chart.

Modulus of deformation values of the soil as well as of the various courses of road structure may be defined directly by circular load tests of the design density and moisture content of the soil or else by inverse calculations of the data resulting from observations of road pavement conditions.

Simultaneously, moisture–temperature conditions of the foundation as well as of the subsoil are studied by special computations of water circulation and concentration and by direct study of moisture content in the foundation.

Sommaire

La répartition des contraintes dans les chaussées multi-couches doit être calculée en tenant compte du degré de rigidité (caractérisé par leur module de déformation), de chaque couche de la chaussée et du sol de fondation. On doit aussi tenir compte du fait que les matériaux constituant la chaussée sont loin d'être parfaitement élastiques.

La force portante d'une chaussée est alors évaluée grâce à sa déformabilité: c'est la charge qui, appliquée sur la chaussée, y provoque une déflection critique. On doit d'ailleurs tenir compte du fait que la déformabilité de la chaussée croît en saison humide, ainsi qu'avec la répétition des charges des camions et des autobus.

Le calcul se fait en deux étapes. En premier lieu, on calcule le module de déformation global ou équivalent de la chaussée considérée dans son ensemble; on calcule ensuite, compte tenu de ce module global, l'épaisseur à donner aux différentes couches.

Les valeurs des modules de résistance des différentes couches du sol et de la chaussée peuvent être mesurées directement par des essais à la plaque chargée, compte tenu de la compacité et de la teneur en eau réelles du sol. On peut aussi, en effectuant les calculs en sens inverse, déduire, des mesures faites sur une chaussée existante, la rigidité de ses couches.

En même temps, on étudie le régime hydrothermique de la fondation de la chaussée et du sous-sol, grâce à des méthodes spéciales de calcul de la circulation et de la concentration de l'eau dans le sol (sous l'effet du climat et du gel notamment). On peut aussi procéder à des mesures directes de teneur en eau dans une chaussée existante.

Design Method

The method of determining the thickness of flexible pavements has been developed under the direction of Professor Ivanov (1943, 1948, 1955). It has been used by organizations concerned with highway design and covered in a graduate course at Technical Institutes of this country for over 10 years (Ivanov, 1952; Birulya, 1954; Autotransizdat, 1949, 1954, 1957). This method has also been used in other countries (Ivanov, 1948; Novotni, 1956; Kézdi, 1954; Babkov *et al.*, 1950). The main principles underlying the method in question are as follows:

Computation of pavement design is based on vertical loads from the dual-tyre wheels of a selected vehicle

$$p = 5 \text{ kg/cm}^2, \quad B = 34 \text{ cm}$$

The traffic intensity of different lorries observed on the road is converted into the equivalent number of selected wheel loads, passenger cars not being taken into account. Horizontal stresses, those of braking included, are assumed to exert no influence on the thickness of the structure. They ought to be taken into consideration when asphalt pavement stability is evaluated.

The bearing capacity of a road structure depends upon a definite ultimate value of vertical displacement of the pavement, increasing only during the wet period of the year (spring season in the north; both winter and spring seasons in the south) by the repeated action of selected wheel loads of moving vehicles.

Ultimate deformation corresponds to the beginning of the failure of the courses in the surfacing or the base, its value depending upon relative thickness of the pavement h/B, the permitted surfacing irregularity and the ease with which it can be restored.

Data from different pavement loading tests have indicated that the ultimate relative vertical deformation can be given by the formula (Fig. 1):

$$\lambda = \frac{\rho}{B} = \frac{0{\cdot}10\nu}{\pi} \text{ arc tan } \sqrt[2{\cdot}5]{\frac{E_1}{E_0}} \cdot \frac{h}{B} \qquad \ldots. \ (1)$$

in which

- ν = a factor ranging from 0·85 to 1·25 depending upon the quality of the pavement and the ease with which the wearing surface can be restored
- ρ = vertical deformation in cm
- B = the diameter of a circular area equivalent to the contact area of the tyre
- h = the thickness of construction
- E_1 = the modulus of deformation of the pavement
- E_0 = the modulus of deformation of the subgrade

The selected relative settlement of pavement for rolled asphalt surfaces is — 0·03; for bituminous macadam — 0·035 to — 0·4; and for macadam and gravel — 0·05.

When evaluating the bearing capacity, multilayer pavements are converted to single ones, being substituted by the equivalent soil course (h_{equiv}), so that the stresses of the subgrade soil remain unchanged.

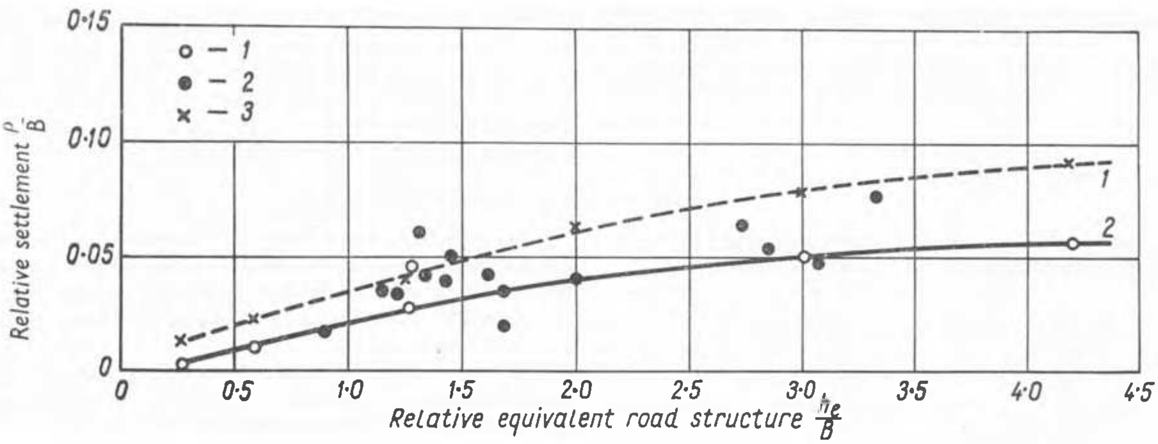

Fig. 1 Relation between the ultimate relative settlement of pavement and its relative thickness h/B: curve 1: rolled asphalt failure; curve 2: after equation 1 for $\nu = 1$—circle: cracks of different pavements

Relation entre le tassement maximum du revêtement et son épaisseur relative h/B: courbe 1: représente la désagrégation du béton bitumineux; courbe 2: d'après la formule 1: pour $\nu = 1$ — le cercle représente les fissures des revêtements

It is a well-known fact that for a two-layer system, in the case of elastic materials, Poisson's ratio is not applicable.

$$h_{equiv} = h\sqrt[3]{\frac{E_1}{E_0}}$$

From road tests of different structures the equivalent layer

$$h_{equiv} = h\sqrt[2\cdot5]{\frac{E_1}{E_0}} \qquad \ldots\ (2)$$

Vertical stress distributions σ_z in the bases of a multilayer pavement are best expressed by the equation

$$\sigma_z = \frac{p}{1 + \left(\frac{h_{equiv}}{B}\right)^2} \qquad \ldots\ (3)$$

where p is the load per unit in kg/cm².

Some decrease in soil stress (as a margin for dynamic effect) resulting from dual-tyre wheel load compared with circular load is not taken into account.

As the actual relation between stresses and settlements deviates from the linear ones, the computations of settlements are based on the values of subgrade modulus of deformation and of other materials obtained for selected relative deformation.

Substituting the values σ and h_{equiv} in the equation

$$\rho = \int_0^\infty \frac{\sigma_z dz}{E}$$

from formulae 2 and 3 we obtain after integration the values for a two-layer system

$$\rho = \frac{pB}{E}\left[\frac{\pi}{2} - \left(1 - \frac{1}{\sqrt[2\cdot5]{\left(\frac{E_1}{E_0}\right)^{3\cdot5}}}\right) \text{arc tan } \frac{h}{B}\sqrt[2\cdot5]{\frac{E_1}{E_0}}\right. \qquad \ldots\ (4)$$

Assuming that $E_0 = E_1 = E_{equiv}$ we have

$$\rho = \frac{\pi p B}{2E_{equiv}} \qquad \ldots\ (5)$$

Equations 4 and 5 permit the evaluation of the multilayer pavement bearing capacity by defining the 'equivalent modulus of deformation', that is, the modulus of deformation of the uniform material which has the deflection equal to that of multilayer structure.

$$E_{equiv} = \frac{E_0}{1 - \frac{2}{\pi}\left(1 - \frac{1}{\sqrt[2\cdot5]{\left(\frac{E_1}{E_0}\right)^{3\cdot5}}}\right) \text{arc tan } \frac{h}{B}\sqrt[2\cdot5]{\frac{E_1}{E_0}}} \qquad \ldots\ (6)$$

Thus, the equivalent modulous f deformation enables us to determine the bearing value of various sections of pavement, meeting at the same time the requirements for pavement strength for different traffic intensities according to equations 7 or 8.

It has been found that the more the actual modulus of deformation deviates from the required value according to traffic intensity, the shorter is the life of the surfacing (Table).

Table

Ratio of the actual modulus of pavement structure to that required according to traffic intensity	*Annual required maintenance in %*	*Relative surfacing life*
1–1·2	0	1
1	2–3	0·95–1
0·9	3–6	0·85–0·95
0·8	6–9	0·50–0·60
0·7	10–20	0·25–0·33
0·5	20–80	—

To take account of structure weakening in the softened subgrade soil and pavements caused by wheel load repetition during the wet period of the year, the coefficient to be introduced in equation 5 must be more than 1.

The effect of the repeated loads becomes evident at a load value in excess of 0·3 to 0·4 of the load value which results in the ultimate deformation at a single load application.

Two series of K values are obtained, namely:

$$K_1 = 0\cdot5 + 0\cdot4 \log N_0 \qquad \ldots\ (7)$$

for repeated loads N_0 on one track at constant moisture content but without frost action and

$$K_2 = 0\cdot5 + 0\cdot65 \log N \qquad \ldots\ (8)$$

resulting from study for average highway traffic where N is the daily traffic intensity on two-lane roads converted to the equivalent number of the selected vehicle.

The deviations from the average coefficient values for different conditions have not yet been obtained.

The conversion of traffic intensities of different types of lorry to those of the selected vehicle is obtained from the equation:

$$\frac{K_1''}{K_2''} = \frac{p_2 B_2}{p_1 B_1} \qquad \ldots\ (9)$$

The calculation of pavement thickness is carried out as follows:

The given actual traffic intensity value having been converted to the selected N, the required modulus E_{req} is determined from the equation:

$$E_{req} = \frac{\pi}{2}\frac{p}{\lambda}(0{\cdot}5 + 0{\cdot}65 \log N)$$

where p is the specific load pressure from the dual-wheel load of the selected vehicle and λ is taken from equation 1.

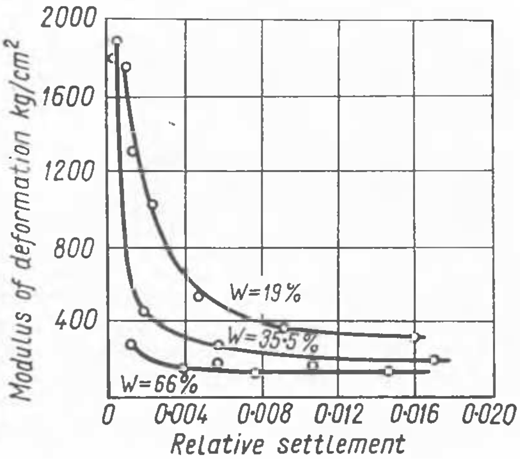

Fig. 2 Modulus of deformation of a sandy-clay soil by different moisture content (W) and different relative settlements (ρ/B). (According to A. S. Smirnov)

Module de déformation pour un sol d'argile sablonneuse ayant différentes teneurs en eau et tassements relatifs (d'après A. S. Smirnov)

E_{req} being known, the thickness of various courses of a multi-layer pavement is derived according to the chart based on equation 6.

The thickness h for a single layer pavement can be determined from equation 6 if the values of E_0, E_1 and B are known. For multilayer pavements, the value of E_0 representing the equivalent value for all the lower courses is successively defined by the chart or equation beginning with the top layers, the bottom course thickness being defined by the chart. This method is also used for the evaluation of the actual equivalent modulus of deformation of the given construction.

Soil Modulus of Deformation

p being known, the modulus of deformation for different λ can be estimated using the theory of elasticity. As a result of the non-linear relation between load and deformation at small deformations, the modulus of deformation value is greater than at larger ones (Fig. 2).

Therefore, the design modulus of deformation for rigid concrete pavements, for example, can be 2 to 2·5 times greater than that in the case of flexible pavement design.

The modulus of deformation value of a subgrade is subject to a number of factors, notably: the depth of seasonal heterogeneity due to the formation of a frozen layer; seasonal humidity variations of the soil particularly as a result of top layers wetting in spring or in autumn; possible heterogeneity of soil compaction at building sites, as well as soil loss of compaction due to frost action.

Thus, the selected modulus of deformation of the subgrade must indicate the properties of multilayer foundations during the most unfavourable period of the year.

The modulus of deformation for the same soil varies depending on the weather conditions of the year. The character of the curves of variation in the value of the soil deformation modulus during the year is seen in Fig. 3, the greatest variation in value occurring during spring soil thawing (Fig. 4).

The minimum modulus of deformation varies depending upon the weather conditions of the year. Therefore, the selection of the design modulus of deformation may be based on the principle of frequency repetition in a given number of years, which is widely used for computing run-off in hydrology.

In a new road construction, average design modulus of deformation value should be admitted since the road foundation does not yet exist when surveying and subgrade design are being carried out. In the reconstruction of roads, the modulus of

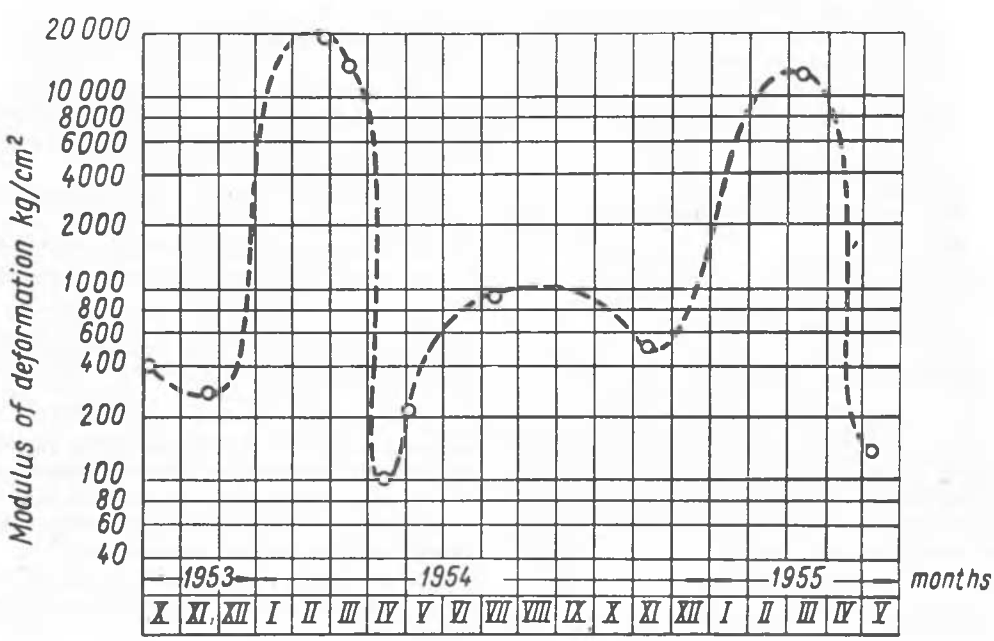

Fig. 3 Annual variations of modulus of deformation of a subgrade (according to I. I. Cherkassov)

Variations pendant l'année du module de déformation du sous-sol de la chaussée (d'après I. I. Cherkassov) deformation should be determined experimentally, by loading tests, during the saturation of the road.

A number of methods for the determination of the modulus of deformation of soils and pavement materials has been lately applied in the Soviet Union.

(1) Theoretical determination according to data of failures of roads during service life or according to data obtained from pavement loading tests (the method of inverse calculations).

(2) Undisturbed soil sample laboratory testing by circular

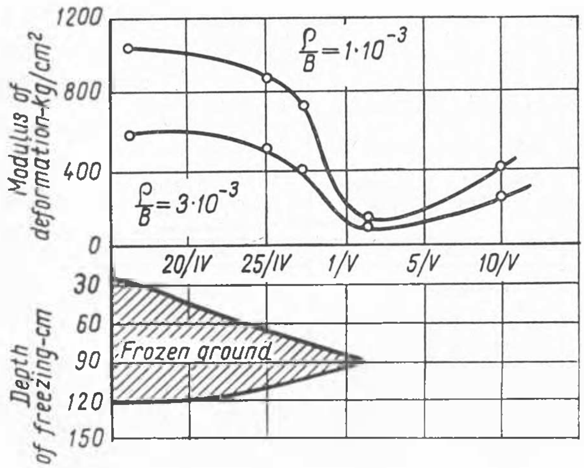

Fig. 4 Variations of modulus of deformation of a subgrade during the spring melting (according to A. S. Smirnov)

Variation pendant le dégel du module de déformation du sous-sol de la chaussée (d'après A. S. Smirnov)

load penetration at the selected moisture content, as an additional method to field testing.

'The inverse calculation method' has for a long time been the basic method of collecting soil and pavement modulus of deformation data, as a method of obtaining the whole picture of a particular character of load action on the road structure,

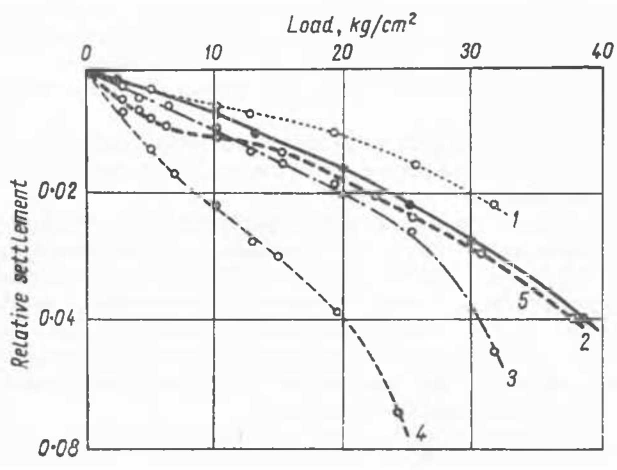

Fig. 5 Relation between load and deformation for different road materials (after M. N. Troizkaya): 1: limestone rubble; 2: rolled asphalt; 3: coal slag; 4: sandstone rubble; 5: burnt clay shale

Rapport entre poids et deformation pour differents matériaux routiers (d'après M. N. Troizkaya): 1: pierres fines de calcaire; 2: Béton bitumineux; 3: laitier de charbon; 4: pierres de grès; 5: schistes d'argile brulées

since it also furnishes information on combined behaviour of both the pavement and subgrade, as well as on the hydrological regional conditions.

To determine the modulus of deformation of rolled asphalt, macadam and gravel surfacings, well compacted large masses of these materials have been used (Fig. 5).

The field tests are accelerated by circular load penetration at a constant speed of deformation (Fig. 6) and also by tests consisting of short-duration application of each series of loads.

From the resulting test data, the modulus of elasticity as well as the period of relaxation are defined, the test results being very promising.

Control of Subgrade Moisture Conditions

Regular moisture and density variations in subgrade soils are due to annual cycles of changes in climatic conditions: soil moisture saturation in autumn; subsequent moisture content distribution in the subgrade during freezing, thawing and drying of subgrade.

According to moisture–temperature characteristics of both the locality and the subgrade, the territory of the Soviet Union is divided into five climatic zones coinciding approximately with typical landscapes and soil zones, namely: the tundra and forest zones, the wet zones; forest and steppe, transitional zones; steppe zones, insufficiently wet; semi-desert, arid zone.

The effect of local moisture sources depending upon the topography and moisture–temperature characteristics are evaluated by the conception of typical localities, notably: with

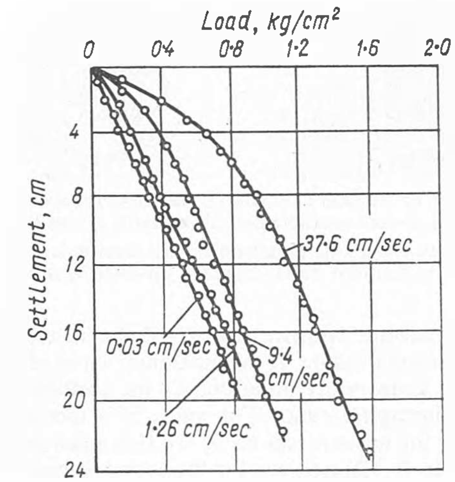

Fig. 6 Relation between the resistance of sandy-clay soil and the settlement of the rigid circular load by constant speed of penetration (according to V. F. Babkov)

Rapport entre la résistance de l'argile sablonneuse et le tassement de la plaque rigide à une vitesse de pénétration constante (d'après V. F. Babkov)

drainage provided and without ground water (dry localities); with excessive moistening by surface waters (localities with temporary humidity); with excessive moistening by ground waters or by combined wetting by surface and ground waters.

It is advisable to maintain, by appropriate design methods, the moisture content of the subgrade at not more than 0·60 to 0·75 of the soil moisture content, which corresponds to the LL.

The moisture content accumulated in the subgrade during the negative temperature period may be derived from the following equations:

(1) For dry localities where moisture content increase in winter occurs essentially on account of vapour condensation and equals approximately

$$\Omega_1 = 2K_F\frac{W_0 - W_1}{0{\cdot}2\alpha}.100 = 1000\frac{J}{\alpha}$$

(as per cent by weight of the soil in per cent of ground weight), where W_0 is the soil molecular moisture capacity, W_1 is the

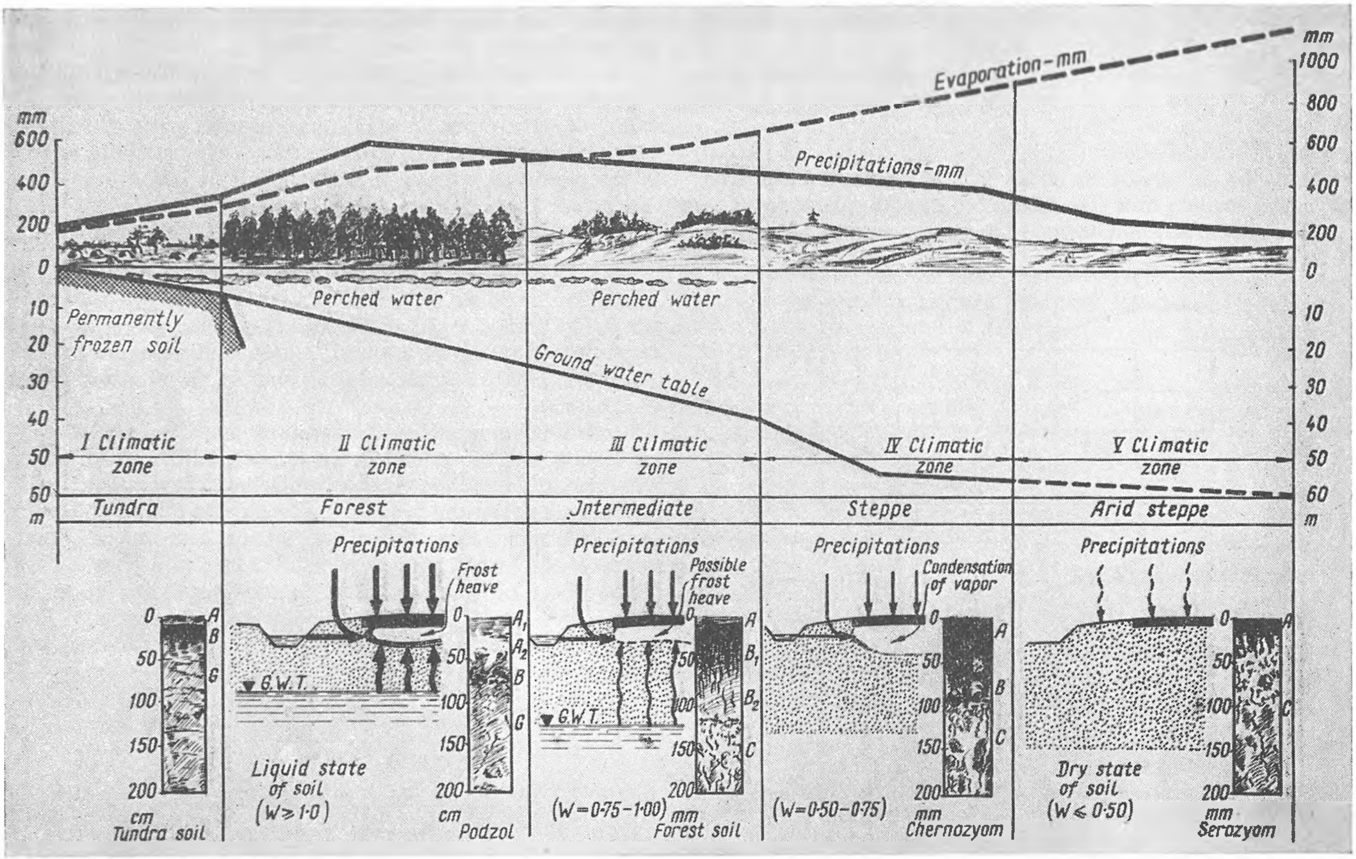

Fig. 7 Changes of moisture content of the subgrade from north to south of the U.S.S.R. *W*: average moisture content in the subgrade in the most unfavourable period (in terms of the LL)

Les changements de la teneur en eau dans le sous-sol de la chaussée du nord au sud de l'URSS. *W*: la teneur en eau moyenne dans le sous-sol de la chaussée pendant la saison la plus impropice (en termes de la LL)

hygroscopic moisture content, $\alpha = H^2/T$ the meteorological index of rate of soil freezing, H the maximum depth of freezing, T the negative temperature duration, K_F the coefficient of soil permeability during freezing. The value of α increases from $\leqslant 50$ cm²/day for western regions of the European part of the Soviet Union to $\geqslant 150$ cm²/day for the eastern regions.

Coarse soils have a low $W_0 - W_1$ value but a higher K_F value, while clay soils on the contrary have a larger $W_0 - W_1$ value but their K_F value is smaller. As a result the product $J = K_F(W_0 - W_1)$ for both soil types is very small, and this sets a definite limit to their moisture accumulation in winter.

The value J has its greatest value in the case of silty and fine-grained sandy soils as well as silty clays and this makes them unsuitable from the point of view of moisture accumulation in winter and frost heave. Moisture increase Ω_1 may amount to 4 per cent, and up to 6 per cent for silty soils of the forest zone.

(2) For the locality with excessive moistening by surface waters, moisture accumulation Ω is produced by capillary water movement

$$\Omega_2 = 80(W_H - W_0)(K_F/\alpha)^{\frac{1}{2}}$$

where W_H is the autumn moisture content which can increase up to 10 per cent in winter.

(3) For the localities with the excessive moistening by ground waters, moisture accumulation may be determined depending upon the freezing depth h_n as well as by the height of embankment edge above the water table.

$$\Omega_3 = 200K_c\frac{(W_c - W_0)}{(H - h_n)}\frac{h_n}{\alpha} = \frac{200J_c h_n}{(H - h_n)\alpha}$$

where W_c is the capillary soil moisture capacity, K_c the capillary moisture conductivity.

Investigations of the moisture–temperature characteristics of the subgrade form the basis for determining questions connected with an increase of the soil modulus of deformation by means of controlling hydrothermal moisture conditions.

Soil moisture control in the upper part of the subgrade consists in:

(1) The provision of subgrade surface water run-off and the stabilization of shoulders with binders to reduce subgrade wetting caused by settlement.

(2) The compaction of soils in the subgrade, particularly in the upper part as well as on shoulders. Artificial compaction of soils in fills is retained for a long time only in the southern regions and in dry places. However, in conditions of surplus moisture in the central and northern regions of the Soviet Union soil compacted to the standard state of compaction tends to swell in the freezing zone if the soil is not carefully insulated from sources of moisture.

(3) A minimum increase of the embankment edge x above the water table or above the soil surface by the provision of a fill or by lowering the water table.

$$x = h_p + \frac{200J_K h_p}{\alpha\Omega_p}$$

where h_p is equal to the soil freezing depth for high-quality roads, and in the case of low-cost roads is equal to depth at which stresses resulting from moving loads cease.

Ω_p is the permissible inflow of moisture as percentage by weight, which fills the soil voids in autumn.

(4) The construction of waterproofing layers (soil stabilized with bitumen).

(5) Drainage layers of porous materials (gravel, sand) for

arresting capillary moisture rise are provided to reduce the height of fill on subgrade sections with surplus moisture.

(6) The drainage layer may be also designed to accumulate all the water coming from below.

References

AUTOTRANOIZDAT (1956). *The Soil Modulus of Deformation Determination.* Moscow

— (1957). *Official Recommendations for Pavement Design.* Moscow

BABKOV, V., GERBOORT-CEIBOVICH, A. and TOOLAEFF, A. (1950). *Soils and Soil Mechanics.* Moscow; Dorizdat (Translations: Prague, 1955; Pekin, 1955)

BIRULYA, A. K. (1954). *The Textbook for Highway design.* Moscow; Autotransizdat

— BIRULYA, V. I. and NOSITCH, I. A. (1951). *Subgrade design in steppe regions.* Moscow; Dorizdat

—(1950). *Design and building of soil foundation for Highway and Railway.* Academy of Science

HOROUNJEF, R. and JOHNES, J. H. (1953). *The design of flexible and rigid pavements.* University of California Press

IVANOV, N. N. and KRIWISSKY, A. M. (1943). *Flexible pavement design.* Moscow; Dorizdat

— (1948). *The textbook for highway building,* Part I. Moscow; Dorizdat (Translations, Warsaw, 1952-53; Pekin, 1951–52)

— *et al.* (1952). *Design data for flexible pavements.* Moscow; Dorizdat

— *et al.* (1955). *Pavement design.* Moscow; Autotransizdat

KÉZDI, A. (1954). *Talaymechanika.* Budapest

NOVOTNI, L. (1956). Flexible pavement design. *Silniče. Obz.*, **1**. Prague

PELTIER, R. (1955). Evaluation de la portance des sols de fondation des chaussées souples. *Rev. gén. Routes.* 278

Proc. 3rd International Conference on Soil Mechanics and Foundation Engineering, 1953

Road Research Laboratory (1952). *Soil Mechanics for Road Engineers.* London; H.M.S.O.

The tenth International Road Construction Congress at Istanbul, section 1—Road Soils