On the Moisture Condition of Highway Subgrade

By

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We cannot design a reliable highway pavement without knowledge of the moisture condition of the paved subgrade because the bearing capacity of subgrade changes much with the moisture condition. Generally, although the moisture condition of bare ground changes much following a change of weather, after the groung is paved, it does not change so much, and is in a limited range.

To know exactly the moisture condition of the subgrade before and after the subgrade is paved, the author investigated the negative pore water pressure in bare and paved ground, and made clear the features of the moisture condition of a typical subgrade. Then the author proposed a new method estimating for the moisture condition of subgrade and an expedient method for estimating the possible wettest moisture condition. As the values estimated by these methods were nearly equal to the measured values, these methods were considered to be usable for designing highway. Especially, the expedient method seemed to be convenient for designing a reliable highway pavement in a rainy country like Japan.

1. Introduction

The moisture condition of subgrade is changed much by the effect of weather before the subgrade is paved. But, after it is paved, the moisture condition reaches a nearly constant condition, i. e. a so-called equilibrium moisture condition. We cannot design an economical and durable highway pavement without knowledge of the bearing capacity corresponding to the moisture condition under future pavement. Thus, it is important to know what the moisture condition of the paved subgrade will be in the future.

In this paper, the author describes the features of the moisture conditions of subgrade before and after paving, from his observations, and proposes a new method for estimating the moisture condition of paved subgrade.

2. The Method used here to research the Moisture Condition of Subgrade

The author investigated the moisture condition of subgrade by measuring the negative pore water pressure with the tensiometer which is illustrated by

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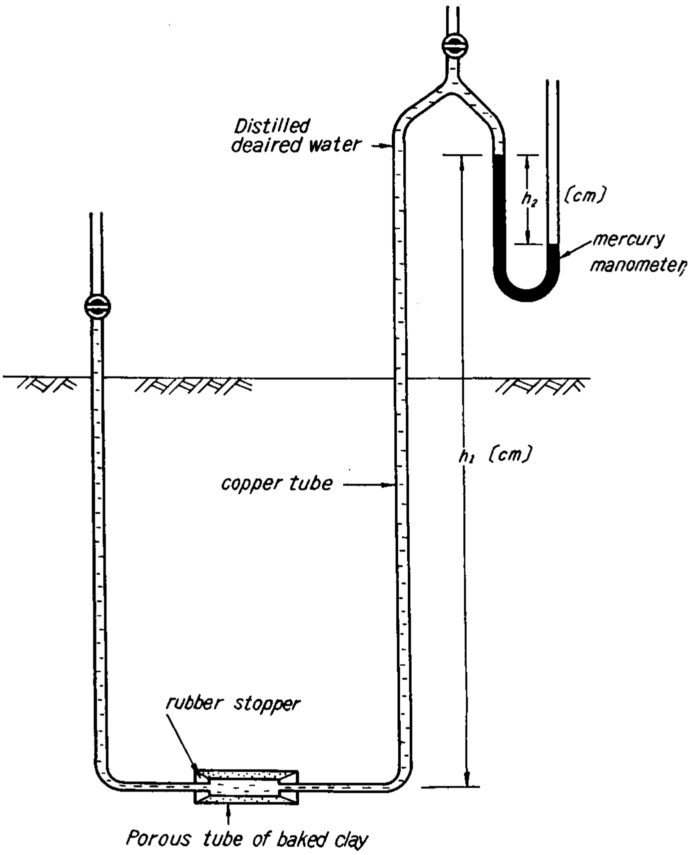


The negative pore water pressure;

$$-u = 13.6\, h_2 - h_1 \quad (\mathrm{g/cm^2})$$

Fig. 1. Illustration of tensiometer used.

Fig. 1. We can know the moisture content of the soil from the negative pore water pressure as follows. First, the negative pore water pressure is converted to the terms of the suction, using the following equation[1]:

$$s = -u + \alpha P \tag{1}$$

where s = the suction of the soil

$-u$ = the negative pore water pressure

P = the total normal pressure

α = the fraction of the normal pressure which is effective in changing the suction.

Then, the suction is converted to the moisture content by using the suction—

moisture content relation curve which has been derived previously through laboratory tests on the subgrade soil in question. The typical relation curves of sand, sandy loam and clay are shown in Fig. 2. These curves were derived by making the specimens dryer first (from zero to 400 g/cm^2 in the suction), and then wetter (from 400 g/cm^2 to zero in the suction). As they have hystersis as shown in Fig. 2, we must use appropriate parts of the curves, considering the history of the soil moisture condition.

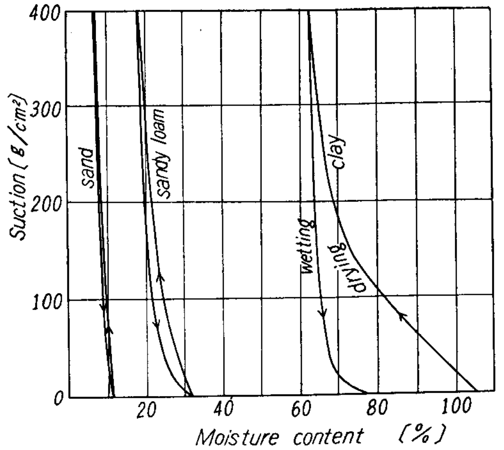


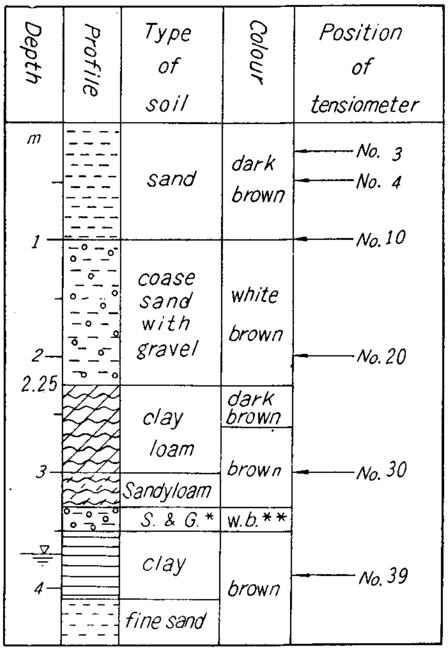
Fig. 2. The typical suction — moisture content curves.

In the case of sand, we can consider the negative pore water pressure to be the same as the suction, because α in equation (1) is zero.

3. The Moisture Condition of Bare Ground

The author set six tensiometers in the bare ground of Kyoto university (the soil profile of which is shown in Fig. 3), at the depths of G.L.-0.25 m, G.D.-0.5 m, G.L.-1.0m, G.L.-2.0 m, G.L.-3.0 m, and G.L.-3.9 m, to investigate the variations of negative pore water pressure in the bare ground. Fig. 3 shows that this ground has a sand layer with some gravel below the ground surface to G.L.-2.25 m, a clay loam layer below G.L.-2.25 m to G.L.-3.30 m, a sand and gravel layer below G.L.-3.30 m to G.L.-3.50 m, a clay layer below G.L.-3.50 m to G.L.-4.10 m, and a fine sand layer below G.L.-4.10 m; and the ground-water level is around G.L.-3.7 m.

Typical data from those tensiometers are shown in Fig. 4. From these data, it is known that the negative pore water



* sand and gravel ** white brown

Fig. 3. The soil profile of investigated ground.

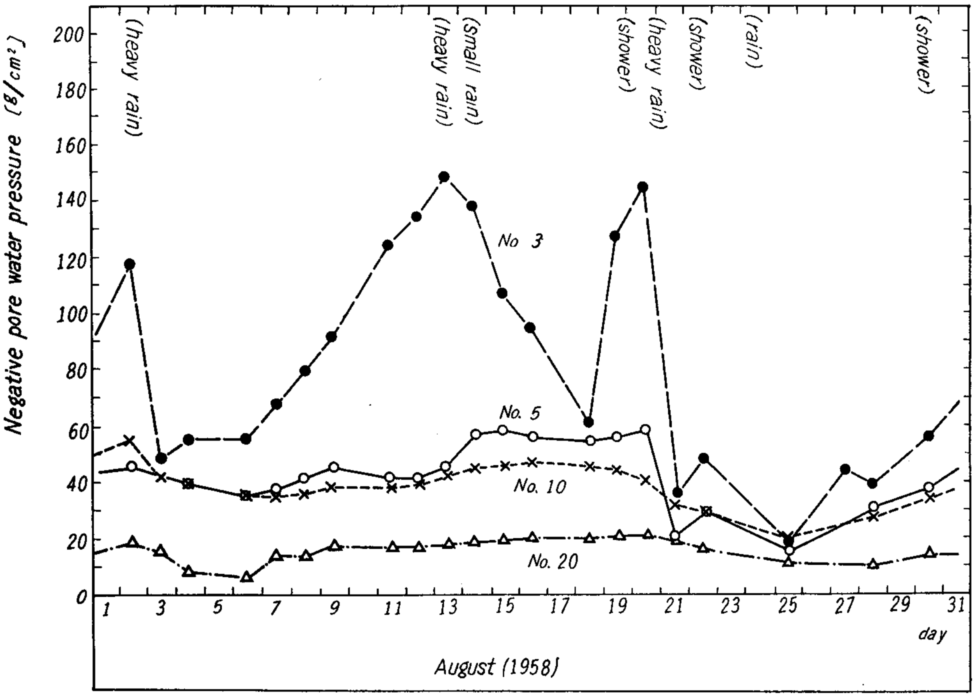
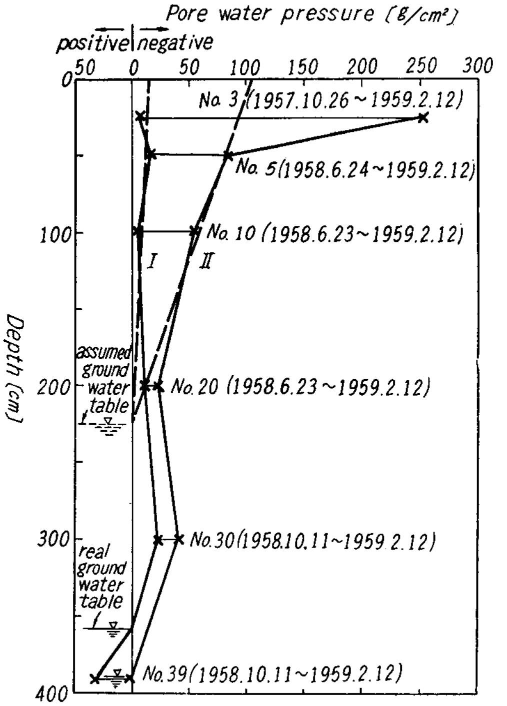


Fig. 4. The typical data by the tensiometers set in bare ground.

pressure decreases rapidly after raining, and increases slowly during fine weather. To inquire into the relationship between the variation range of negative pore water pressure and depth from the ground surface, the maximum and minimum measured values at each depth are plotted against depth as shown in Fig. 5. In Fig. 5 it is seen that the variation range of negative pore water pressure decreases as the measured point is deeper, and the negative pore water pressure at G.L.-2.0 m is almost unvarying, and is near to zero. This fact seems to be due to the fact that the upper boundary of clay loam at G.L.-2.25 m is acting as an assumed groundwater table because the permeability of the lower layer (G.L.-2.25 m~G.L.-3.30 m) is very small as compared with the upper layer.

Next, to make clear the variation of negative pore water pressure during a year, the mean values for each ten days and for each month are plotted as shown in Fig. 6. From the graph wich shows the mean values, for each month it seems that the negative pore water pressure is generally higher, i.e. the moisture content is lower, in summer than in winter. But we can never overlook the variations during short terms because their range is larger than the monthly one,



Note: The numbers in parentheses show the observation periods.

Fig. 5. The relationship between the variation range of pore water pressure and depth from the ground surface.

4. The Moisture Condition of Paved Ground

It has been considered that the soil moisture condition of subgrade reaches a constant condition after the pavement is laid because the causes of disturbance through the ground surface for soil moiture, e.g. infiltration of rain water and evaporation, are removed by the pavement. This phenomenon may be exactly real under the inner part of very wide pavement. But in the case of comparatively narrow pavement, the moisture condition may change even under the inner part of the pavement following changes in weather.

To know exactly the moisture conditions under pavement, the auther set three tensiometers under

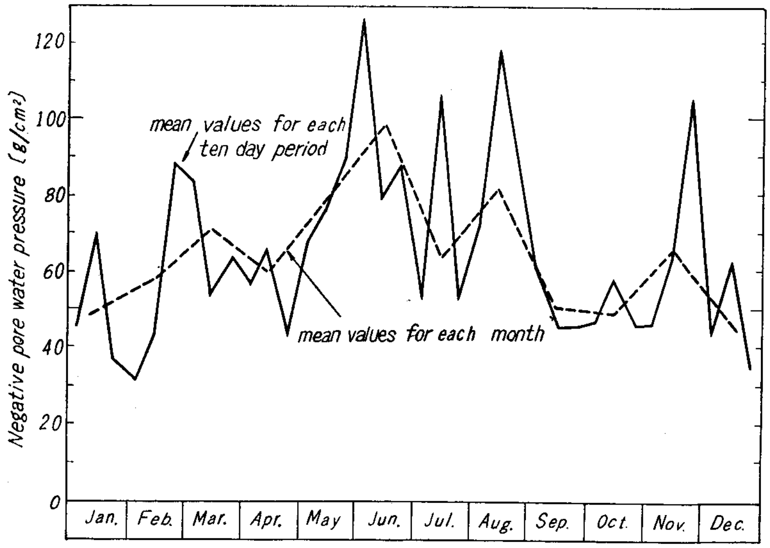


Fig. 6. The variation of negative pore water pressure during a year.

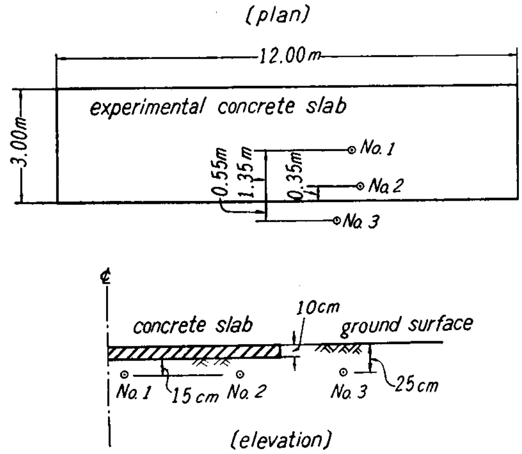


Fig. 7. The measured points by tensiometers under and near the pavement.

and near an experimental concrete slab which was laid on the ground of Kyoto university. This slab was 3 m in width and 12 m in length. As shown in Fig. 7 the No. 1 tensiometer was set under the approximate center of the pavement width, the No. 2 tensiometer was set under a spot 0.35 m in from the edge of the pavement, and the No. 3 tensiometer was set in the ground 0.55 m from the pavement edge—all three at a depth of 15 cm from the base of the slab. Fig. 8 gives typical data showing daily changes of the negative pore water pressure at No. 1, No. 2, and No. 3 tensiometers. Fig. 8 shows us that although the negative pore water pressure changes greatly outside of the pavement, the pressure under the inner part of the pavement changes only slightly and keeps a nearly constant condition. But we cannot overlook the fact that there is some influence of

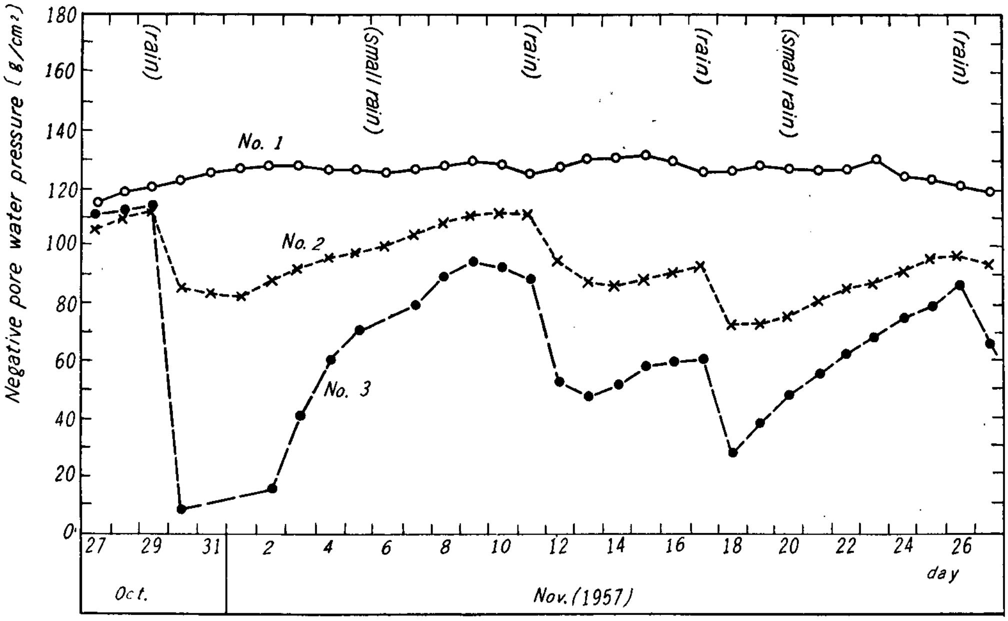


Fig. 8. The typical data showing daily change of the negative pore water pressure under and near the pavement.

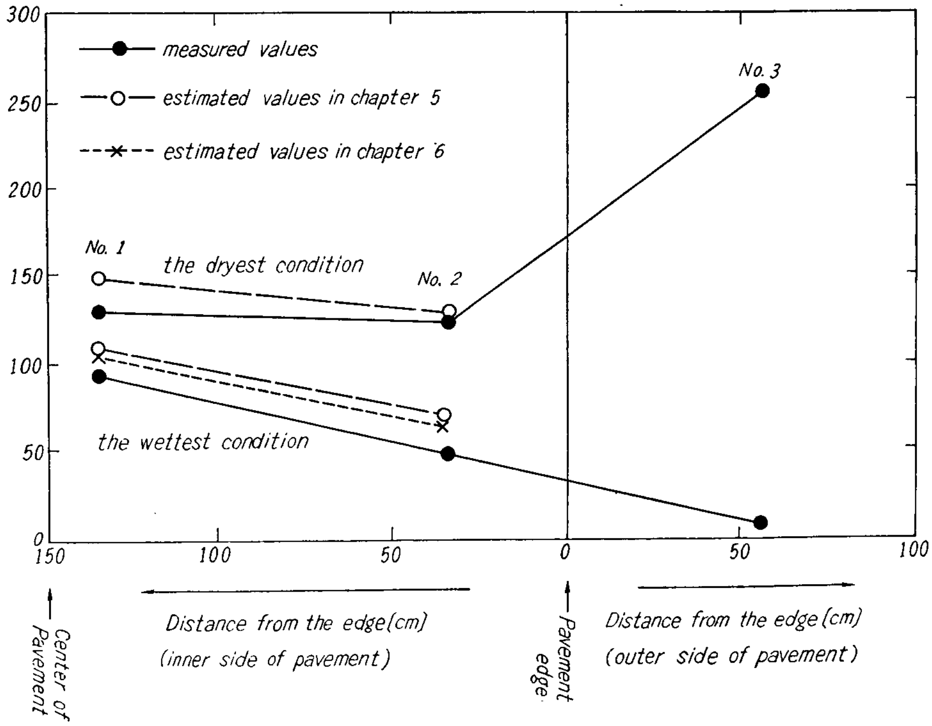


Fig. 9. Relationship between the variation range of negative pore water pressure and the position referring to the pavement.

weather through the pavement edges even under the pavement. This fact is shown well by Fig. 9 which is drawn from the maximum and minimum pore water pressure measured by the No. 1, No. 2 and No. 3 tensiometers. The decrease of the variation range of pore water pressure with distance from the pavement edge is similar to the decrease with depth from the ground surface, as we see by referring to Figs. 5 and 9.

The wettest and dryest moisture conditions shown in Fig. 9 can be estimated by the method described in the next chapter. For engineering purposes generally it is important to know the wettest condition of a subgrade, because it corresponds to the lowest bearing capacity of the subgrade. The possible wettest condition of paved subgrade can be estimated more easily by the expedient method explained in chapter 6.

5. On a New Method for Estimating the Moisture Condition of Paved Subgrade

Up to this time there have been several methods for estimating the moisture condition of paved subgrade, e.g. the method based on the moisture content at about 1 m depth[2], the method using the results of investigation of old paved subgrade which has the same boundary conditions as the planned one, the method using moisture content corresponding to about 100 g/cm^2 in suction[3], the method assuming that the pavement has infinite width[1], and others.

As the methods mentioned above were only empirical or incomplete theoretical methods neglecting the influence of weather through the pavement edges, the author devised a new theoretical method using measurable boundary conditions, i.e. width of pavement, moisture condition at pavement edges, groundwater level, etc.

To find the general moisture condition of paved subgrade, we must solve the fundamental equation of soil moisture matching the subgrade's boundary conditions. The fundamental equation of soil moisture can be derived from the equation of continuity and the equation of momentum as follows.

$$\frac{\partial}{\partial t}(\gamma_d \cdot w) = \nabla \cdot (\gamma_w \cdot k \cdot \nabla \Phi) \qquad (2)$$

where γ_d = the dry density of the soil

w = the moisture content of the soil

γ_w = the density of the soil moisture

k = the permeability of the soil

Φ = the total head which is the sum of the elevation head and the pressure head of the soil moisture.

Although, for general moisture condition, we must analyse equation (2) to agree with the boundary conditions, it is very difficult to solve this equation rigorously because of changes in permeability as a function of moisture content, dry density and type of soil and because of changes in boundary conditions. But to know the wettest and dryest moisture conditions of paved subgrade it is enought to solve equation (2) at assumed steady conditions. From this standpoint, we are going to solve the following equation instead of equation (2).

$$\nabla^2 \Phi = 0 \qquad (3)$$

We can estimate the moisture conditions of paved subgrade at the wettest and dryest limits by solving equation (3) using boundary conditions of ground water table, width of pavement and assumed moisture boundary conditions, which are effective for the inner part of the subgrade, at pavement edges in the wettest and dryest seasons.

Now the author will explain this estimating method, applying it to the subgrade under the experimental concrete pavement described in the preceding chapter. In this case, the width of pavement is 3 m, and there is an assumed groundwater level at G.L.-2.25 m, and the coefficient of permeability of the subgrade can be considered as uniform from the ground surface to G.L.-2.25 m as found in chapter 3 and 4. The moisture boundary conditions, which are effective for the inner part of the subgrade, are estimated at pavement edges as 14 g/cm^2 and 106 g/cm^2 in terms of the negative pore water pressure for the wettest and dryest conditions by using the broken lines I and II in Fig. 5. Thus we assume that the moisture is flowing in steady state through the bare ground from the surface to the groundwater table under the distribution of total head shown by the broken line I or II in Fig. 10 for the wettest or dryest condition. The distributions of moisture total head in the subgrade under the pavement surrounded by the bare ground mentioned above are obtainable, as shown in Fig. 11 for the wettest condition, and in Fig. 12 for the dryest condition, by using the relaxation method or the experiment of electrical analogy. The distributions of negative

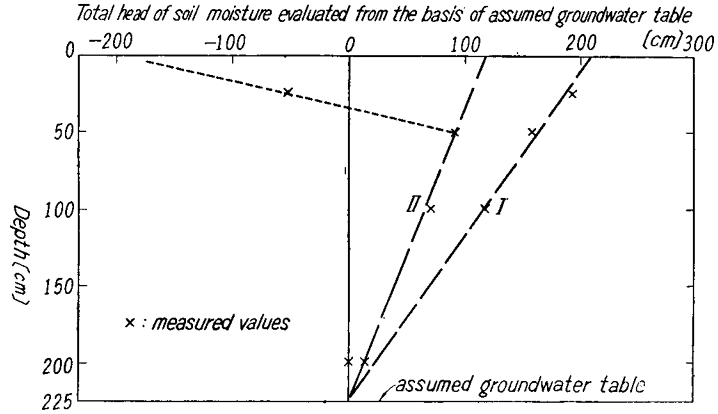


Fig. 10. Assumption of total head distribution in bare ground to solve the example in chapter 5.

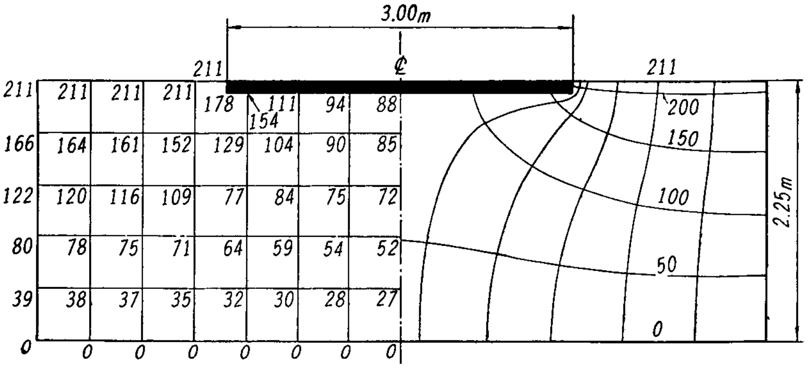


Fig. 11. The distribution of the moisture total head in the paved subgrade at the wettest condition.

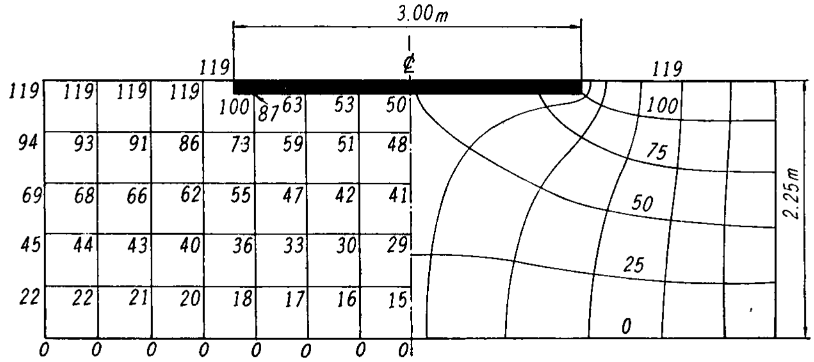


Fig. 12. The distribution of the moisture total head in the paved subgrade at the dryest condition.

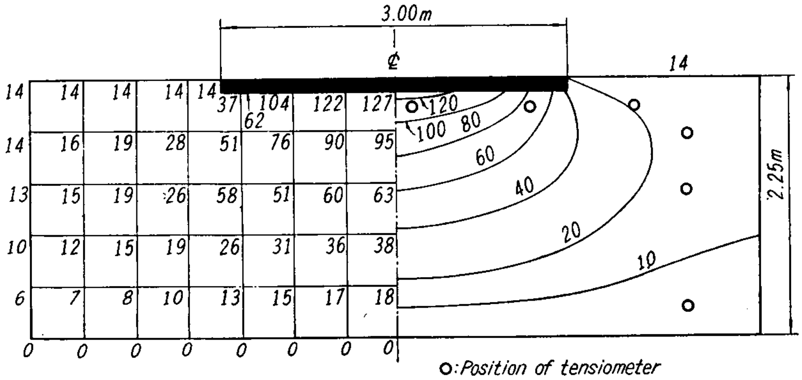


Fig. 13. The distribution of the negative pore water pressure in the paved subgrade at the wettest condition.

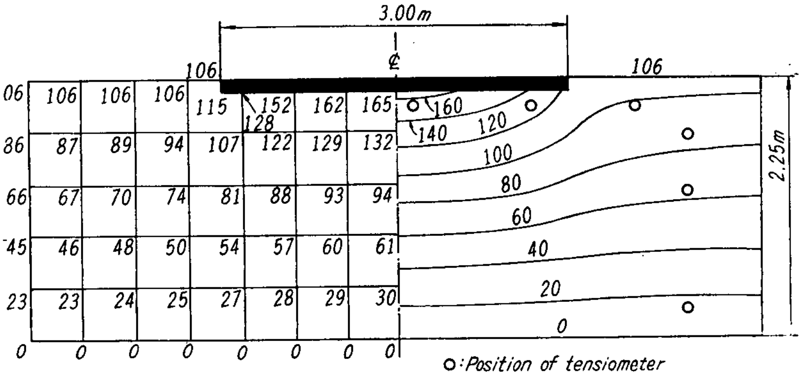


Fig. 14. The distribution of the negative pore water pressure in the paved subgrade at the dryest condition.

pore water pressure can be got by eliminating each elevation head from the distributions of total head as shown in Figs. 13 and 14, and we can estimate the negative pore water pressures at the positions of the No. 1 tensiometer and the No. 2 tensiometer. The estimated values and the measured values are compared in Fig. 9. It is considered that the reason why all the estimated values are somewhat higher than the measured values is because of neglect of the well permeable gravel subbase 5 cm thick directly under the pavement. But it seems that this estimating method is superior to the old ones in its accuracy.

6. On an Expedient Method for Estimating the Wettest Moisture Condition of Paved Subgrade

In the estimating method mentioned in the preceding chapter, generally it is somewhat troublesome to gain correctly the assumed moisture boundary conditions at pavement edges through observations over a long period. But for highway in rainy country, it may be allowable to assume that the moisture boundary condition at the pavement edges is zero in regard to the negative pore water pressure. Thus we can estimate the possible wettest moisture condition. Estimating the wettest moisture condition on this expedient assumption for the experimental paved subgrade mentioned in the preceding chapter, we get the dotted line in Fig. 9. Although there is a little difference between these estimated wettest values, which are solved neglecting the 5 cm thick gravel layer directly under pavement, and the measured ones in Fig. 9, this expedient estimating method is considered to be usable for reliable design of highway pavement in rainy country.

7 Conclusion

The author measured the negative pore water pressure in bare and paved ground for a little over a year, using tensiometers. The negative pore water pressure can be easily converted into the terms of the suction and the moisture content. In the bare ground, the negative pore water pressure varied greatly from the ground surface to about 50 cm depth, but below that it did not change much. The negative pore water pressure was high in summer and low in winter; but its short time changing range was larger than the variation range for months' mean values, according to data from the tensiometer set at G.L.-25 cm. The soil moisture condition under the pavement did not vary much, but it was recognized to vary as a result of the influence of precipitation and evaporation received through the pavement edges. From the author's observation, it was found that the decrease in the variation range of pore water pressure in the paved ground with distance from a pavement edge was similar to the decrease with depth from the ground surface in the bare ground.

Although the old methods for estimating the moisture condition in paved subgrade were only empirical or incomplete theoretical methods, neglecting the influence of weather through the pavement edges, the author devised a new estimating method for the wettest and dryest moisture conditions considering the measurable boundary conditions, i.e. groundwater level, width of pavement, moisture condition at pavement edges, etc. Further, the author proposed an expedient method for estimating the possible wettest moisture condition. As the values estimated by this method were nearly equal to the measured values, this method was considered to be usable for designing highway. Especially, the expedient method for estimating the possible wettest moisture condition seemed to be useful for designing durable highway in a rainy country like Japan.

This paper is a summary of a part of the author's dissertation for his doctor's degree, " Study on the Moisture Condition and Bearing Capacity of Subgrade ", at Kyoto university.

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