Influences of freeze-thaw on performance of pavement structures in snowy cold region

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ABSTRACT

This paper examines the effects of freeze-thaw and water content on the deformation-strength properties of subbase course materials to evaluate the mechanical behavior of granular base in cold regions. Water retention tests of freeze-thawed subbase course materials, CBR tests of freeze-thawed subbase course materials under various water contents, and resilient modulus tests in unsaturated condition were conducted using three newly developed test apparatuses. Moreover, these results were compared with long-term field measurement at a model pavement structure, including FWD tests. As the results, it was revealed that the deformation-strength characteristics of unbound subbase course materials degrade due to freeze-thaw and increment of the water content in thawing season. This indicates that the freeze-thaw of granular base has a strong influence on the fatigue life of pavement structures.

Keywords: freeze-thaw action; unsaturated soils; laboratory element tests; SWCC; CBR; MR

1 INTRODUCTION

In snowy cold regions like Hokkaido, Japan, frost heave and swelling of pavement surface, or cracking in asphalt-mixture layer. Such phenomena specific to cold regions are thought to accelerate deterioration of pavement structures. Recently, a theoretical design method that can take the above-mentioned degradation of pavement structures into consideration has come to be used as a structural design method of asphalt pavement in cold regions. However, the frost-heave phenomenon and the temporary degradation in the bearing capacity during thawing season have not been sufficiently elucidated as well as the modelling of these phenomena. To develop an optimal design method against fatigue failure of asphalt pavement in Japan, it is necessary to understand the mechanical behavior of subgrade and base course during freeze-thaw in detail. This paper examines the effects of freeze-thaw action and water content on the deformation-strength characteristics of subbase course materials to evaluate the change in mechanical behavior of granular base caused by freeze-thaw and concurrent seasonal fluctuations in water content.

2 FIELD MEASUREMENT IN COLD REGIONS

Long-term field measurement and FWD (Falling Weight Deflection) tests were conducted at a test pavement (4 m width × 14 m length) in Hokkaido, a cold and snowy island in northern Japan, as shown in. Fig. 1. The subbase course layer and the anti-frost layer are constituted of natural, angular, hard andesite crusher-run, which are commonly used in Japanese pavement structures. The physical properties and grain size distributions are shown in Fig. 2, respectively.

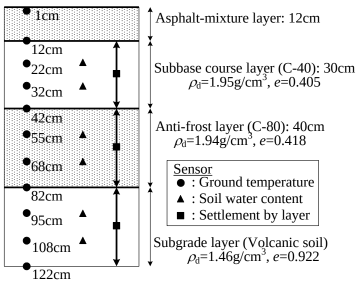

Fig. 1. Test pavement for field measurement.

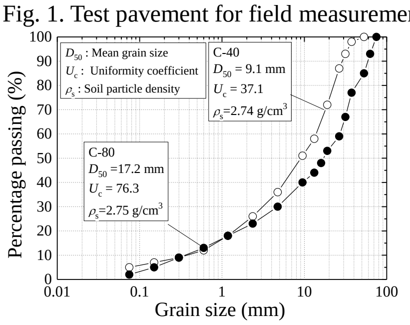

Fig. 2. Grain size distribution of subbase course materials.

According to Fig. 3(a), the average daily temperature remains below 0 °C during roughly 3 months from mid-December to early March in both years, and the frost-penetration depth decreased dramatically as the temperature rises starting in mid-March. The frost-penetration depth reached only the center of subbase course in 2008 due to high average temperature, while it reached the anti-frost layer in 2009. In Fig. 3(b), there is an apparent tendency for the degree of saturation to decrease rapidly after late December in 2009, when the frost-penetration depth increased dramatically. It was, however, higher after

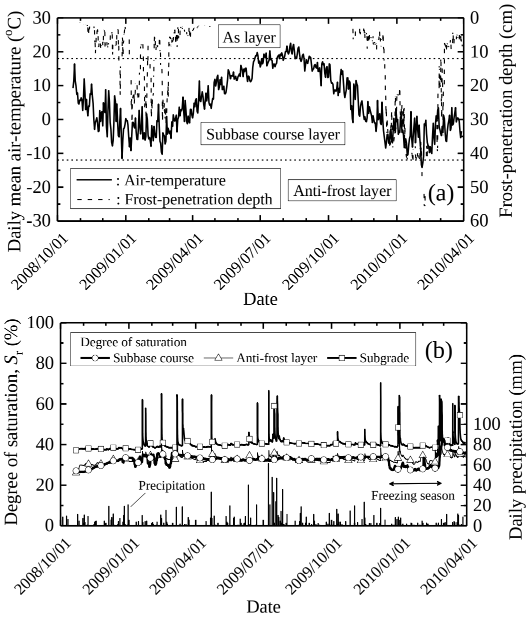

Fig. 3. Results of long-term field measurement.

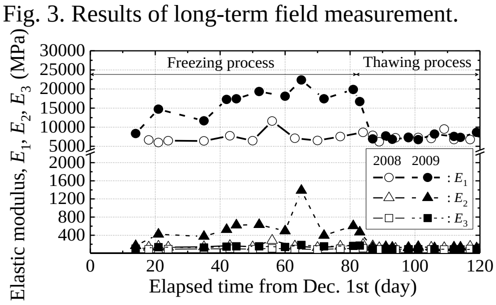

Fig. 4. Temporal transitions in the elastic moduli.

thawing than before freezing. Therefore, the water content of subbase course tends to be almost constant, except the rapid decrease during the freezing season and the temporary increase during the thawing season and after rainfall.

Based on the results of FWD tests, the elastic modulus for each layer of the pavement using the static back-analysis program BALM (Matsui et al. 1998) was estimated. The temporal transitions in the elastic moduli, E_1, E_2, and E_3, for As layer, base layer, and subgrade layer, respectively, are shown in Fig. 4. No large changes in elastic modulus are observed at any layer in 2008. On the other hand, the elastic moduli of all layers increased as the temperature dropped, and then decreased rapidly from late February, when the temperature began to rise in 2009 to reach the same level as that in 2008. Comparing the fluctuations in elastic modulus to the changes in ground temperature and soil water content, a clear temperature dependency is observed for E_2. It increases as the average ground temperature decreases after dropping to 0 °C or below. This is the result of increased stiffness caused by the freezing of the base. Besides, it is evident that E_2 decrease slightly when the degree of saturation increases when the base is not frozen.

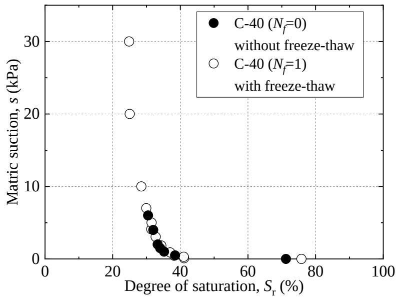

Fig. 5. Soil-water characteristic curves of C-40.

3 LABORATORY ELEMENT TESTS

3.1 Water retentivity of subbase course materials

A freeze-thawing water retention test apparatus can perform water retention tests for freeze-thawed coarse granular materials by using suction method under low suction range and pressure method under high suction range, and it adopts a small-height test specimen and two drainage paths with both ceramic disk and membrane filter to reduce total testing time. A water retention test on a specimen exposed to freeze-thaw action were conducted. An air-dried specimen was prepared by compacting the air-dried C-40 sample with a vibrator at a degree of compaction (D_c) of 90%, and it was saturated by permeating water to achieve a capillary-saturated specimen. After the one-dimensional consolidation under an overburden pressure (σ_a) of 10.0 kPa, freeze-thaw of the specimen was conducted according to JGS 0172-2003. Finally, a water retention test was carried out using suction method and pressure method as per JGS 0151-2009.

Fig. 5 compares the difference in the soil water characteristic curve (SWCC) during the drying process of C-40 without and with freeze-thaw history. It is noted that based on the results of freeze-thaw CBR tests of C-40 discussed later, the frost-susceptibility of C-40 is considered to be low regardless of freeze-thaw history and water content. The difference in SWCCs between a freeze-thawed specimen and a no freeze-thawed specimen can hardly be recognized. This is because the dry densities before and after consolidation are nearly equal and the grain size distributions remain unchanged even if the specimen is subjected to freeze-thaw, and because frost heave was not confirmed. These results indicate that the freeze-thaw action has little influence on the water retention characteristics of subbase course materials.

3.2 CBR of subbase course materials

A freeze-thawing CBR (California Bearing Ratio) test apparatus is an improved one to reproduce the freeze-thaw history experienced by the subbase course materials in a real pavement structure, in a laboratory environment. CBR tests on the specimens exposed to different patterns of freeze-thaw history under three different water contents were conducted. The specimen was prepared by compacting the air-dried C-40 sample

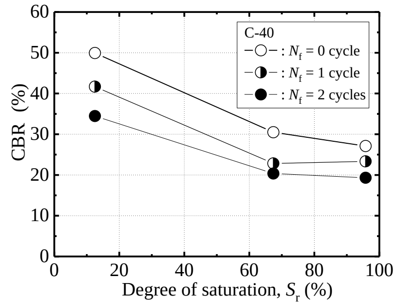

Fig. 6. CBR values under different test conditions.

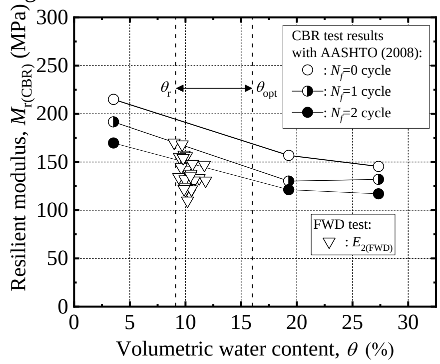

Fig. 7. Influence of water content on resilient modulus.

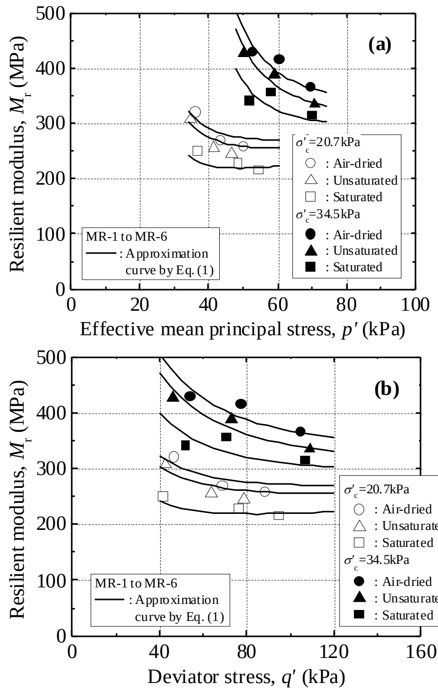

Fig. 8. Resilient moduli under different test conditions.

with a vibrator at a degree of compaction (D_c) of 95% ("air-dried"). Then, air-dried specimens were saturated by permeating water ("saturated"), and successively saturated specimens were allowed to drain by gravity ("wet"). A freeze-thaw CBR test of C-40 was conducted as follows. Freeze-thaw of the specimen was performed according to JGS 0172-2003, though this research adopted closed-system freezing so that the initial water content of the specimen could be maintained. The freeze-thaw process was repeated. After subjection to the freeze-thaw history, CBR test was carried out as per JIS A1211 (2009).

Fig. 6 shows the relationships between CBR and initial volumetric water content (θ) under different number of freeze-thaw process cycles (N_f). The overall tendency shows a decrease in CBR caused by the increase in water content. Comparing test results of specimens without freezing to examine differences due only to water content, CBR is found to decrease to nearly 50% when the condition changes from air-dried to saturated, indicating that the water content has an extremely major influence on CBR. Whereas, a drop in CBR accompanied by an increase in N_f is observed regardless of water content. In particular, the ratio of decreasing CBR tends to become larger with the decrease in water content. Fig. 7 compares the resilient modulus ($M_{r(\mathrm{CBR})}$) estimated by Eq. (1) (AASHTO 2008) with the elastic modulus of base layer (E_2) calculated from the above-mentioned FWD test results.

$$M_r = 17.6 \cdot \mathrm{CBR}^{0.64} \tag{1}$$

The variation range for $M_{r(\mathrm{CBR})}$ under cyclic freeze-thaw actions approximately coincides with that for E_2 when the water content is similar. Accordingly, it seems reasonable to conclude that Eq. (1) adopted in the AASHTO standard has high applicability in the evaluation of the resilient modulus of subbase course layer in Japanese pavement structures.

3.3 Resilient moduli of subbase course materials

A medium-size triaxial apparatus for unsaturated soils adopts pressure membrane method for reducing total testing time by applying matric suction from both ends of the specimen. Besides, it can perform water retention tests, triaxial compression tests and resilient modulus test (MR test) for unsaturated soils to evaluate the deformation-strength characteristics of coarse granular materials. MR tests on C-40 were performed under three different water contents as follows. An air-dried specimen after compaction (D_c=95%) and a saturated specimen after permeation were isotropically consolidated under an effective confining pressure (σ_c') of 49.0 kPa. An unsaturated specimen after the isotropic consolidation of a capillary-saturated specimen under a net normal stress (σ_{net}) of 49.0 kPa was produced by applying a matric suction (s) of 10 kPa. Upon attaining an equilibrium condition in the consolidation process, MR tests were performed under fully drained condition (CD test) in conformance with the AASHTO Designation: T307-99.

Fig. 8 shows the relationships between the resilient modulus (M_r) and the effective mean principal stress (p') or the deviator stress (q), respectively, obtained from MR tests on C-40 under different water contents. Besides, the regression analysis results of Eq. (2) (Yau and Quintus 2002) are also shown in the figure.

$$M_r = k_1 p_a \left(\frac{\sigma_{ii}}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{p_a}+1\right)^{k_3} \tag{2}$$

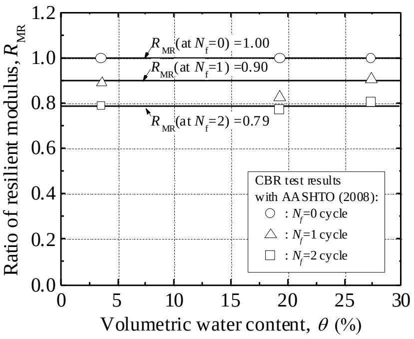

Fig. 9. Ratio of resilient modulus under various water contents.

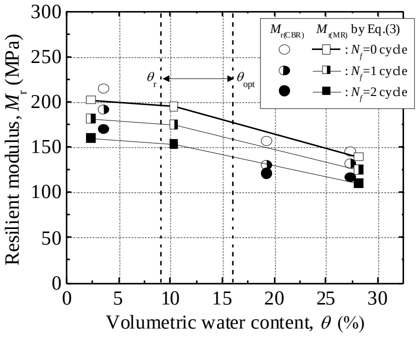

Fig. 10. Applicability of proposed simple estimation formula.

Where, k_1, k_2, k_3 are regression constants, σ_{ii} is bulk stress, p_a is normalizing stress, and τ_{oct} is octahedral shear stress. When comparing plots with the same p' and q under the same σ_c', the remarkable decreasing tendency of M_r followed by the increase in the water content is recognized irrespective of σ_c'. The stress-dependency of M_r obtained from MR tests qualitatively agrees well with the regression results by Eq. (2), regardless of the water content.

3.4 Effects of freeze-thaw and water content on M_r

To evaluate the influences of the freeze-thaw action on the resilient modulus of subbase course materials with various water contents as shown in Fig. 7, a resilient modulus constitutive equation is newly proposed by assuming that the effect of the cyclic freeze-thaw actions on M_r is represented by the compensation function $f(N_f, \theta)$ as shown in Eq. (3).

$$M_r = f\left(N_f, \theta\right) \cdot k_1 p_a \left(\frac{\sigma_{ii}}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3} \tag{3}$$

Fig. 9 compares the ratios of $M_{r(\mathrm{CBR})}$ for a freeze-thawed specimen at a given N_f against $M_{r(\mathrm{CBR})}$ for an unfrozen specimen at N_f=0, which is defined as "ratio of resilient modulus (R_{MR})", under various water contents to quantitatively analyze the effect of the water content and freeze-thaw history on the compensation function $f(N_f, \theta)$. The effect of the water content on R_{MR} cannot be clearly discerned irrespective of N_f, though R_{MR} gradually decreases to a value lower than 1 with the increase in N_f, regardless of the water content. Therefore, the effects of θ on the compensation function $f(N_f, \theta)$ is negligible enough, and it is considered that the average value of R_{MR} could be adopted as the value of $f(N_f, \theta)$ for each N_f.

Fig. 10 compares $M_{r(\mathrm{CBR})}$ with the resilient modulus ($M_{r(\mathrm{MR})}$) estimated by Eq. (3). Note that this stress conditions was selected so that $M_{r(\mathrm{MR})}$ approximately coincides with $M_{r(\mathrm{CBR})}$ for unfrozen specimens with the same water content. Although the $M_{r(\mathrm{MR})}$ is a little lower than $M_{r(\mathrm{CBR})}$ when the water content was high, Eq. (3) seems to reproduce the overall tendency for the resilient modulus to decrease in concurrence with the increase in water content and number of freeze-thaw process cycles. Therefore, it seems reasonable to conclude that Eq. (3) is sufficiently applicable to the quantitative evaluation of the resilient modulus for unsaturated subbase course materials subjected to repeated freeze-thaw actions at the pavement structures in cold regions, Japan.

4 CONCLUSION

The following findings can be mainly obtained:

- There is a close relationship between freeze-thaw action and seasonal fluctuation in water content, and the change in the stiffness of granular base
- Freeze-thaw action has little influence on the water retention characteristics of subbase course materials.
- Resilient modulus increases during freezing and decreases during thawing, due to the decrease and increase in water content.
- Freeze-thaw action affects the fatigue life of pavement structures in cold regions.

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