Effect Evaluation of Freeze-Thaw on Deformation-Strength Properties of Granular Base Course Material in Pavement

Évaluation des effets de gel-dégel sur les propriétés de résistance à la déformation des matériaux granulaires de couche de base des chaussées

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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. CBR tests of freeze-thawed subbase course materials under various water contents, and the resilient modulus tests in unsaturated condition were conducted using two 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 granular base course materials deteriorate 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.

RÉSUMÉ: Cet article examine les effets de gel-dégel et de la teneur en eau sur les propriétés de résistance à la déformation des matériaux de couche de fondation de chaussée pour évaluer le comportement mécanique des bases granulaires dans les régions froides. Des essais CBR de gel-dégel des matériaux de couche de fondation de chaussée avec diverses teneurs en eau, et des essais de module résilient, dans des conditions non saturées, ont été réalisés à l'aide de deux appareils récemment mis au point. De plus, ces résultats ont été comparés, avec les mesures de terrain à long terme, à un modèle de structure de chaussée, y compris des essais FWD. Les résultats ont mis en évidence que les caractéristiques de résistance à la déformation, des matériaux granulaires de couche de base non liés, se détérioraient en raison du gel-dégel et de l'accroissement de la teneur en eau durant la saison de dégel. Ceci indique que le gel-dégel des bases granulaires a une forte influence sur la durée de vie en fatigue des structures des chaussées.

KEYWORDS: unbound granular base course matrials, freeze-thaw action, unsaturated soil, CBR test, triaxial test

1 INTRORDUCTION

In snowy cold regions such as Hokkaido, the 0 °C isotherm may penetrate deep into pavement, thereby causing 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 and losing of the functions. Recently, a theoretical design method that can predict the long-term performance of transportation infrastructures has come to be used as a structural design method of asphalt pavement in cold regions. The theoretical design method can take the above-mentioned degradation of pavement structures into consideration. However, the frost-heave phenomenon and the temporary degradation in the bearing capacity during the 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 behaviour 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 behaviour of granular base caused by freeze-thaw and concurrent seasonal fluctuations in water content, and the influences on fatigue life of pavement structures. For that reason, we developed a freeze-thawing CBR test apparatus and a medium-size triaxial apparatus for unsaturated soils. CBR tests of freeze-thawed subbase course materials under various water contents, and the suction-controlled resilient modulus (MR) tests in unsaturated condition were carried out. Moreover, this paper compares results of the above-mentioned laboratory element tests with those of long-term field measurement at a model pavement structure, including FWD tests.

2 TEST APPARATUS

2.1 *Freeze-thawing CBR test apparatus*

A schematic diagram of a freeze-thawing CBR (California Bearing Ratio) test apparatus is shown in Figure 1. This test apparatus is based on a general CBR test apparatus that has been improved to reproduce the freeze-thaw history expected to be applied to subbase course materials at the in-situ pavement structures, in a laboratory environment. It has following features:

– The apparatus, which allows free water absorption or drainage (open-system freezing) or suppresses it (closed-system freezing) during the freeze-thaw process, can perform a frost-heave test compliant with “Test Method for Frost Heave Prediction of Soils (JGS 0172-2003)” on a CBR test specimen (∏=150mm, H=125mm).
– Since the temperatures of both ends of the specimen are controlled independently, the apparatus can subject a CBR test specimen to a desired one-dimensional freeze-thaw history at a constant freezing rate (moving speed of frost line).

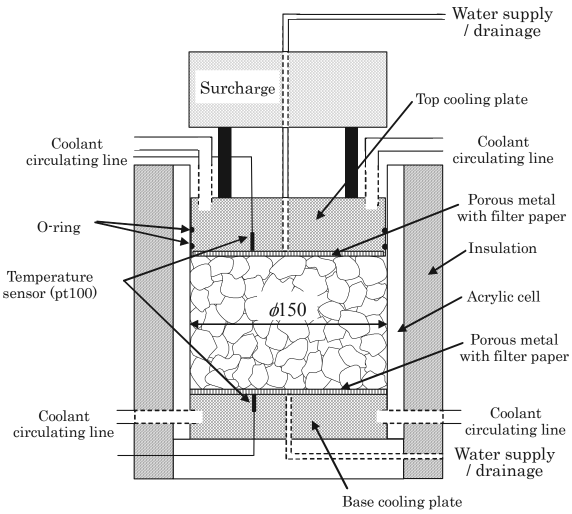

Figure 1. Freeze-thawing CBR test apparatus.

- Since the apparatus can conduct a CBR test immediately after the freeze-thaw process without moving the sample, the effects of the freeze-thaw action on the bearing-capacity characteristics of unbound granular base course materials can be examined under clear boundary condition, as well as the initial conditions.

2.2 *Medium-size triaxial apparatus for unsaturated soils*

A schematic diagram of a medium-size triaxial apparatus for unsaturated soils is shown in Figure 2. One key feature of the apparatus is the structural design of the cap and pedestal as shown in Figure 2. Here, the versapor membrane filter is a kind of microporous membrane filters made from hydrophilic acrylic copolymer, and polyflon filter is a hydrophobic filter made from polytetrafluoroethylene. The other key features are as follows:

- Since the apparatus can use a medium-size cylindrical specimen (ϕ=150mm, H=300mm), a triaxial compression test can be performed in accordance with the "Standard Method of Test for Determining the Resilient Modulus of Soils and Aggregate Materials (AASHTO Designation: T307-99)" (AASHTO, 2003).
- The apparatus can apply the matric suction from both ends of the specimen (Figure 2). Besides, pore water is allowed to drain from both cap and pedestal. Accordingly, the apparatus can reduce the testing time by shortening the length of drainage path to half of the specimen height, in addition to the effect of versapor membrane filter.
- The apparatus can apply axial load to a specimen with high accuracy by both strain control method and stress control method with only one hybrid actuator. Moreover, the apparatus can perform both monotonic loading tests with very slow loading rate, and cyclic loading tests in which the maximum frequency of cyclic loading is up to about 10 Hz.

3 METHODOLOGY

3.1 *Method of freeze-thaw CBR test*

CBR tests on the specimens exposed to different patterns of freeze-thaw history under three different water contents were conducted by using the newly developed freeze-thawing CBR test apparatus. As a test sample of the CBR test, a natural crusher-run (C-40, Figure 3) made from angular, crush, hard andesite, which is employed at the subbase course of pavement structures in Japan, was used. The specimen was prepared by compacting the air-dried samples (water content, w=1.8%) with a vibrator at a degree of compaction (D_c) of 95% ("air-dried condition"). Then, air-dried specimens were saturated with permeating water for 1 hour ("saturation condition"), and after the saturation process saturated specimens were allowed to

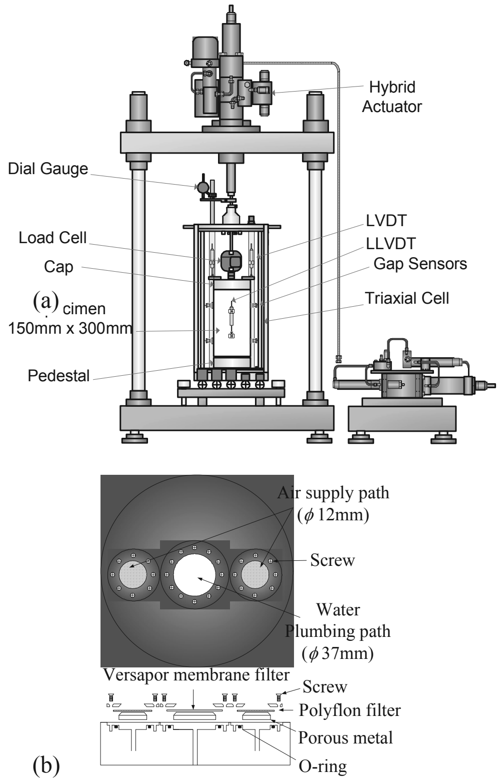

Figure 2. Medium-size triaxial apparatus for unsaturated soils.
(a) Schematic diagram of test apparatus.
(b) Structural design of cap and pedestal.

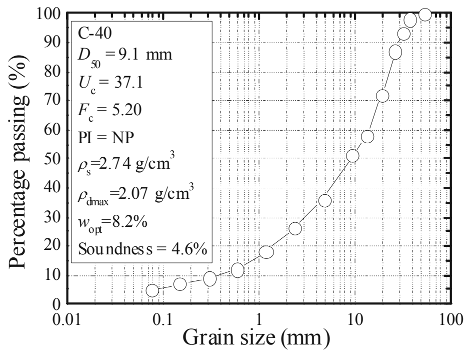

Figure 3. Physical properties of subbase course material.

drain by gravity for 3 hours ("wet condition"). Therefore, there were three types of specimens defined by the difference in initial water content.

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, and the number of freeze-thaw process cycles (N_f) was given in three patterns of N_f=0 (no freezing), 1, and 2 cycles. After subjection to the freeze-thaw history, CBR test was carried out as per Japanese Industrial Standards "Test Method for the California Bearing Ratio (CBR) of Soils in Laboratory (JIS A 1211: 2009)".

3.2 *Resilient modulus test*

Cyclic loading triaxial compression tests on C-40 were performed under three different water contents in conformance with the AASHTO Designation: T307-99 by using the newly developed medium-size triaxial apparatus for unsaturated soils as follows. In the air-dried condition (w=1.2%), an air-dried specimen after compaction (D_c=95%) was isotropically consolidated under an effective confining pressure (σ_c') of 49.0

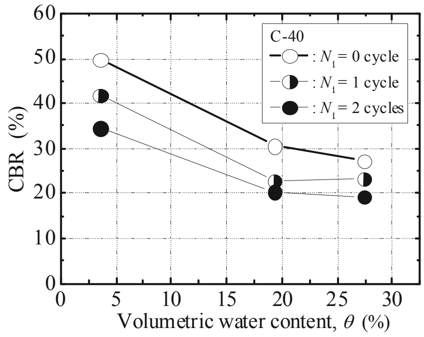

Figure 4. Results of freeze-thaw CBR tests.

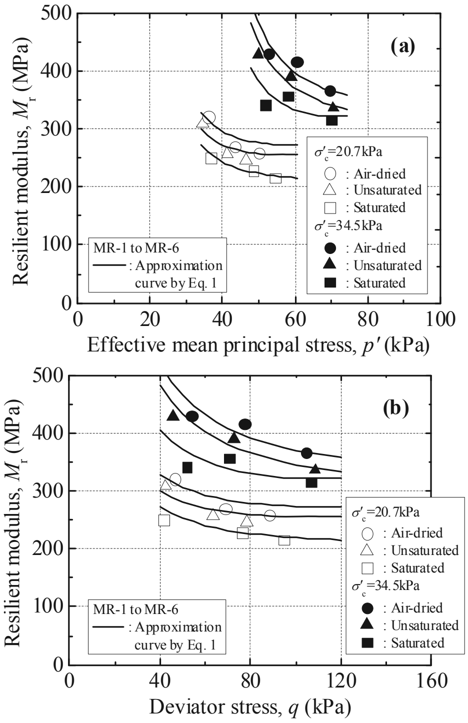

Figure 5. Results of resilient modulus tests.

kPa. In the saturated condition (w=14.3%), a saturated specimen after compaction (D_c=95%) and permeation was isotropically consolidated under σ_c' of 49.0 kPa. In the unsaturated condition (w=5.3%), first, after compaction (D_c=95%) and permeation, a capillary-saturated specimen was isotropically consolidated under a net normal stress (σ_{net}) of 49.0 kPa by applying confining pressure (σ_c) of 249 kPa, pore air pressure (u_a) of 200 kPa and pore water pressure (u_w) of 200 kPa. Here, σ_{net} is defined as $\sigma_{net}=\sigma_c-u_a$. Next, an unsaturated specimen under a matric suction (s) of 10 kPa was produced by decreasing u_w while keeping both σ_c and u_a constant. Here, s is defined as $s=u_a-u_w$. Upon attaining an equilibrium condition in the consolidation process, MR tests were performed under fully drained condition (CD test) as follows. For repeated loading, a haversine-shaped load pulse with a load duration of 0.1 sec followed by a rest period of 0.9 sec was applied. A MR test requires both conditioning process with 1000 loading cycles (N_c) followed by actual testing process with 100 loading cycles under 15 successive paths with varying combinations of confining pressure and deviator stress.

4 RESULTS AND DISCUSSIONS

4.1 *Results of freeze-thaw CBR tests*

The frost heave rate (U_h), which is used as a frost-susceptibility index, was U_h=0.1mm/h or lower for all test conditions, and thus frost-susceptibility of C-40 is considered to be low

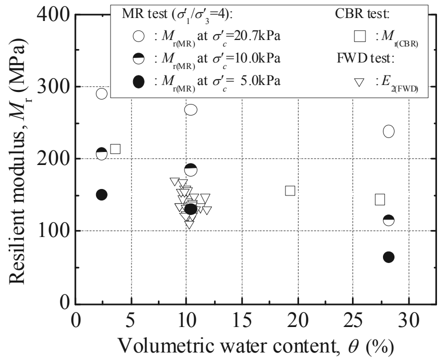

Figure 6. Influence of water content on resilient modulus.

regardless of the freeze-thaw history and the soil water content. Whereas, Figure 4 shows the relationships between CBR and initial volumetric water content (θ) under different N_f. The overall tendency shows a decrease in CBR caused by the increase in water content. Comparing test results of specimens without freezing (N_f=0) 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. On the other hand, a drop in CBR accompanied by an increase in the number of N_f is observed regardless of the water content. In particular, the ratio of decreasing CBR tends to become larger with the decrease in the water content. The volumetric water content at the subbase course in an actual pavement structure is lower than that of the specimen in wet condition (Ishikawa et al. 2012). Thus, it is expected that the influence of the freeze-thaw action on the bearing-capacity of granular base course materials is more pronounced in in-situ condition.

4.2 *Results of resilient modulus tests*

Figure 5 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. Here, M_r is defined as q_{cyclic}/ε_r (q_{cyclic} : amplitude of repeated axial stress, ε_r : amplitude of resultant recoverable axial strain due to q_{cyclic}). Note that the test data in unsaturated condition was arranged by using σ_{net} instead of σ_c' in air-dried and saturated conditions. Besides, the regression analysis results of Eq. 1, which is utilized as a resilient modulus constitutive equation in the MEPDG (AASHTO 2008), are also shown in the figure.

$$M_r = k_1 p_a \left(\frac{\sigma_{ii}}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{p_a}+1\right)^{k_3} \quad \text{(Yan and Quintus 2002)} \qquad (1)$$

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. For plots with the same σ_c', M_r decreases with the increase in p' and q, while for plots with the same p' and q, M_r increases with the increase in σ_c'. A dominant effect for the deformation behavior of C-40 is an increase in M_r with increasing confining pressure, regardless of water content. On the other hand, 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 this research qualitatively agrees well with the tendency of past researches like the regression analysis by Eq. 1, regardless of the water content.

4.3 *Effects of freeze-thaw and water content on M_r*

Under different water contents, Figure 6 compares the resilient modulus ($M_{r(CBR)}$) estimated by the following empirical formula (Eq. 2) based on the correlation between CBR and M_r, with the resilient modulus ($M_{r(MR)}$) derived from the regression analysis results as shown in Figure 5. Note that $M_{r(MR)}$ are estimated by assuming the stress state, calculated using multi-layered elastic

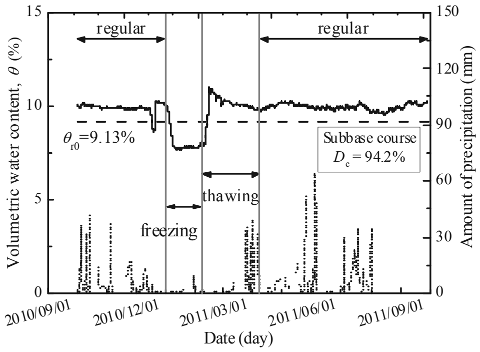

Figure 7. Results of long-term field measurement

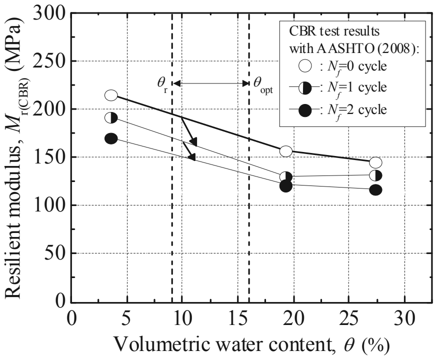

Figure 8. Resilient modulus estimated from CBR test results.

analysis (Ishikawa et al. 2012), at an actual Japanese pavement structure. The elastic moduli ($E_{2(FWD)}$) for subbase course layer calculated from FWD test results using the static back-analysis program BALM (Matsui et al. 1998) are also plotted against the volumetric water content (θ) measured at the long-term field measurement (Figure 7).

M_r=17.6·CBR$^{0.64}$ (AASHTO 2008) (2)

The decreasing tendencies of all types of M_r with increasing water content are in fair agreement with each other, irrespective of the calculation method. Though $M_{r(MR)}$ noticeably depends on σ_c' in case of the same water content, $M_{r(MR)}$ estimated at σ_c' of 10 kPa closest to the in-situ overburden pressure is almost equal to the upper limit of $E_{2(FWD)}$. Besides, $M_{r(CBR)}$ approximately coincides with $M_{r(MR)}$ when the principal stress ratio (σ'_1/σ'_3) is 4 under the σ'_c of 10.0 kPa, irrespective of θ. Accordingly, it seems reasonable to conclude that the suction-controlled MR test results in this research quantitatively match those in previous laboratory element tests and field measurement, and 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.

Figure 8 shows the relationships between $M_{r(CBR)}$ and initial volumetric water content (θ) under different N_f. Note that the range from residual volumetric water content (θ_r) to θ_{opt} correspond to optimum water content obtained from a water retentivity test and compaction tests on C-40 (Ishikawa et al. 2012) is indicated in the figure. The overall tendency is identical to that observed in Figure 4. When being focused on the range, a decrease in $M_{r(CBR)}$ due to the increase in the number of freeze-thaw process cycles is severe as compared with a decrease in $M_{r(CBR)}$ due to the increase in water content. Besides, according to results of long-term field measurement (Figure 7), it is expected that the resilient modulus of subbase layer at the actual pavement structure deteriorates along the path shown by the arrows in Figure 8 when it is exposed to repeated freeze-thaw and the concurrent seasonal fluctuations in water content. Therefore, freeze-thaw action seriously influences the resilient deformation characteristics of granular base course materials and hence it also affects the fatigue life of pavement structures in cold regions.

5 CONCLUSIONS

The following findings can be mainly obtained:

- Two new test apparatuses have high applicability in the evaluation of the deformation-strength characteristics of granular base course materials exposed to repeated freeze-thaw and concurrent seasonal fluctuations in water content.
- A dominant effect for mechanical behavior of base course materials in cold regions is a decrease in the CBR and the resilient modulus with increasing water content and freeze-thaw action, and with decreasing confining pressure.
- Empirical formulas adopted in AASHTO standards have sufficient applicability in evaluation of resilient modulus of subbase course layer in Japanese pavement structures.
- Decreasing tendencies of resilient modulus against water content derived from MR tests, CBR tests, and FWD tests qualitatively and quantitatively agree well with each other.

These indicate that when developing a theoretical model for predicting the mechanical behavior of pavement structures in cold regions, it is important to give a special consideration to the degradation in the bearing capacity and resilient modulus caused by cyclic freeze-thaw actions even in non-frost susceptible granular base, in addition to the effects of an increase in water content during the thawing season. However, further examination of the validity, limitation of application and so forth needs to be conducted in the future in order for the outcomes of this research to be practically applicable.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

AASTHO. 2003. Standard Method of Test for Determining the Resilient Modulus of Soils and Aggregate Materials. AASTHO Designation T 307-99. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*, T307-1-T-307-41.

AASHTO. 2008. *Mechanistic-Empirical Pavement Design Guide: A Manual of Practice*. Washington.

Ishikawa, T., Kawabata, S., Kameyama, S., Abe, R., and Ono, T. 2012. Effects of freeze-thawing on mechanical behavior of granular base in cold regions. In Miura, Ishikawa, Yoshida, Hisari & Abe (eds), *Advances in Transportation Geotechnics II*, Proc. intern. conf., Sapporo, 10-12 September 2012, 118-124.

Ishikawa, T., Zhang, Y., Segawa, H., and Miura, S. 2012. Development of medium-size triaxial apparatus for unsaturated granular base course materials. In Miura, Ishikawa, Yoshida, Hisari & Abe (eds), *Advances in Transportation Geotechnics II*, Proc. intern. conf., Sapporo, 10-12 September 2012, 185-191.

Japanese Geotechnical Society. 2003. Test method for frost susceptibility of soils (JGS 0172-2003). *Standards of Japanese Geotechnical Society for Laboratory Soil Testing Methods*, 45-50.

Japanese Standards Association. 2009. Test Method for the California Bearing Ratio (CBR) of Soils in Laboratory (JIS A 1211: 2009). *Japanese Industrial Standards*. (in Japanese).

Matsui, K., Kurobayashi, I. and Nishiyama, T. 1998. Effort for improving accuracy of pavement layer moduli estimated from FWD test data. *Journal of Pavement Engineering* 3, 39-47. (in Japanese).

Yan, A., and Quintus, H. L. V. 2002. *Study of LTPP Laboratory resilient modulus test data and response characteristics: Final Report*. Publication No. FHWA-RD-02-051, U.S. Dept. of Transportation, Federal Highway Administration, McLean, VA, 1-161.