Testing method for resilient properties of unsaturated unbound granular materials subjected to freeze-thaw action

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ABSTRACT

Resilient modulus ($M_r$), the ratio of the amplitude of cyclic axial stress to the amplitude of the resultant recoverable axial strain, is especially important in mechanistic pavement design procedure and it usually decreases in thaw season. This loss of stiffness was attributed to the change of moisture and the effect of freeze-thaw has not been considered completely. This paper proposed a new test method for resilient modulus of unsaturated unbound granular materials subjected to freeze-thaw action. By controlling the matric suction stable during freeze-thaw process, the water content before and after freeze-thaw is constant. As a result, the effect of freeze-thaw on resilient modulus could be studied. Test results illustrate that freeze-thaw process not only reduces resilient modulus greatly, but also weakens the influence of bulk stress, deviator stress, and matric suction on resilient modulus, even with same water content before and after freeze-thaw. Besides, a freeze-thaw process also leads to a smaller Secant Young’s modulus and a larger permanent axial strain under repeated axial loads.

Keywords: resilient modulus, freeze-thaw, degree of saturation, subgrade material

1 INTRODUCTION

Resilient modulus ($M_r$) is especially important in mechanistic pavement design procedure and considerable researches had been conducted since Seed et al. (1955) proposed the concept of resilient modulus as the ratio of the amplitude of cyclic axial stress to the amplitude of the resultant recoverable axial strain. The resilient modulus in cold regions like Hokkaido is strongly affected by the occurrence of seasonal frost, while most studies aim to explore the effects of moisture, density, and stress conditions on the resilient modulus, meanwhile, the freeze-thaw effect is not fully investigated.

Johnson et al. (1978), Cole et al. (1981), Berg et al. (1996), and Simonsen et al. (2001, 2002) conducted a series of resilient modulus tests (MR tests) of frozen, thawed, and recovered granular materials. Basically, they found there is a significant loss of stiffness from frozen to thawed, and an increase in the recovery period. Meanwhile, this loss of stiffness in thaw season is mainly attributed to the change of moisture. The effect of freeze-thaw has not been considered separately, which implies a requirement for further investigation.

To check the effect of freeze-thaw on mechanical properties of unsaturated unbound granular materials, Ishikawa et al. (2010, 2012) developed a triaxial apparatus which could apply freeze-thaw on the test specimen.

This paper proposes a testing method for evaluating the effect of freeze-thaw on the resilient properties of unsaturated unbound granular materials by applying one-dimensional freeze-thaw action on an unsaturated specimen and controlling the matric suction at the same time to ensure the water content is constant before and after freeze-thaw.

2 TEST APPARATUS AND MATERIAL

2.1 Test apparatus

The test apparatus used in this study is shown in Fig. 1, which consists of a cyclic triaxial test apparatus that can apply cyclic axial loads, and three low-temperature baths which could circulate low-temperature fluids (antifreeze) in the cap, pedestal, and inner cell separately to control the temperature. The size of the specimen is 170 mm in height and 70 mm in diameter. The vertical displacement of the specimen is measured with an external displacement transducer. The temperature of the cap and pedestal is measured with a thermometer. Axial stress is measured by the load cell. The volume of water drainage is measured with a double tube burette and a differential pressure transducer. Confining pressure, pore water pressure, and pore air pressure are measured with pressure transducers.
**2.2 Test material**

Toyoura sand was used as test materials. Toyoura sand is a type of Japanese standard sand, employed as a test material by many researchers in laboratory element tests. It is classified as a poorly graded sand (SP) according to ASTM classification. Toyoura sand is a non-frost-susceptible material. Specimens were prepared by air pluviation method and the degree of compaction \(D_c\) was 96% and dry density \(\rho_d\) was 1.58 g/cm\(^3\) to satisfy the standard of Japanese Ministry of Land, Infrastructure, Transport and Tourism. By confirming the pore pressure coefficient \(B\) is 0.96 or more, a fully-saturated condition was ensured. Thereafter, isotropic consolidation was carried out with a predetermined consolidation stress of 41.4 kPa, which is the same as the highest confining pressure in the MR test (AASHTO 2003).

**3 TEST METHODS**

**3.1 Water retentivity test**

To check the validity of the newly developed apparatus, a water retentivity test is necessary. The test method for the water retentivity test is as follows.

Versapor membrane filters soaked in a laboratory dish filled with de-aired water were placed within a triaxial cell. To saturate the filters, a negative air pressure of -90 kPa was applied to the triaxial cell for 24 hours. Then, install the versapor membrane filter on the pedestal. Meanwhile, de-aired water was flushed from the base plate to remove air inside the water plumbing path. Polyflon filter was affixed on the cap by grease. The detail of versapor and polyflon filters are shown in following Table 1.

After preparing the specimen with oven-dried Toyoura sand (water content is treated as zero) by air pluviation method, it was permeated from the bottom end by de-aired water through a double tube burette to measure the water content. When no more water gets into the specimen, start the back pressure by increasing pore-water pressure, pore-air pressure, and confining pressure step by step to 200, 200, and 249 kPa respectively.

**Table 1. Properties of filters employed.**

| Name of filter | Directions for use | Thickness (μm) | Pore size (μm) | k (m/s) |
|---------------|-------------------|----------------|---------------|---------|
| Versapor      | Plunging path     | 94             | 0.8           | 60      | 4.4×10\(^{-5}\) |
| Polyflon      | Air supply path   | 500            | NA            | 3.9     | NA      |

Then, a water retentivity test was initiated at a nearly saturated condition, and it proceeded through a drying process by decreasing pore-water pressure in steps, while keeping both confining pressure and pore-air pressure constant. A decrease of pore-water pressure equals an increase of matric suction, causes the drainage of pore water from the specimen. Upon attaining an equilibrium condition, the drainage was stopped and the water content corresponding to the applied matric suction was computed by reading the change in water volume during each increment in matric suction with a double tube burette. The above-described procedure was then repeated for higher values of matric suction until the desired range for the drying curve in soil-water characteristic curve (SWCC) was obtained.

**3.2 Resilient modulus test**

According to the long-term field measurement data (Ishikawa et al. 2012), the volumetric water content of a subgrade layer in Hokkaido is about 16%. Hence, the unsaturated specimen used in present study also has a 16% degree of saturation, which corresponds to a 3.75 kPa matric suction according to the SWCC of Toyoura sand (Fig. 3). It is noted that subgrade material in Hokkaido is usually volcanic soil but not Toyoura sand.

Three types of resilient modulus tests are conducted as unsaturated freeze-thaw test, freeze-thaw unsaturated test, and unfrozen unsaturated test.

In unsaturated freeze-thaw test, after obtaining the SWCC, an unsaturated specimen is prepared with similar steps by applying a determined matric suction value on the specimen and waiting for the equilibrium condition. With a constant matric suction value, temperatures of the cap, pedestal, and inner cell are controlled by circulating low-temperature fluids in the cap, pedestal, and inner cell separately. The initial temperature of cap and pedestal were set to 0°C and 16.8°C respectively. The thermal shock was applied at the top end of the specimen prior to freezing to avoid supercooling. Meanwhile, the pedestal temperature was kept at 16.8°C. Then, the temperature of cap and pedestal were lowered to -18.9°C and -2.1°C in 11.5 hours respectively with a constant cooling rate of -1.64°C/hr. Next, the temperature of cap and pedestal were kept for 5 hours to ensure the
uniformity of unfrozen water. The thawed status was achieved by raising the temperature of cap and pedestal to 0°C and 16.8°C in 11.5 hours with a heating rate of 1.64°C/hr. Open-system freeze-thaw process, which means the specimen could drain and supply water, was used in this test by opening the pedestal water plumbing path during the freeze-thaw process. Referring to JGS 0172-2009 (Japanese Geotechnical Society 2009), applied axial stress during the freeze-thaw process was set as 10 kPa. MR test will be started when the freeze-thaw action is finished. MR tests are performed according to AASHTO T307-99 (American Association of State Highway and Transportation Officials 2003). A haversine wave load pulse with a frequency of 0.2 Hz and without rest time was applied. AASHTO T307-99 uses haversine wave load pulse with a frequency of 10 Hz and also has a 0.9 second rest time. The number of load cycles of MR-0 was prolonged to 2000 cycles to ensure a constant residual strain after MR-0. Besides, the vertical stress in stage MR-4, 5, 9, and 10 are significantly larger than the stress measured in the actual situation (Kishikawa et al. 2017). The overstress in MR-4, 5 increased the relative density and the results of MR -6, 7, 8 cannot be evaluated accurately. To sustain the relative density, we decreased the deviator stress, and the details of applied stress and number of load cycles are shown in Table 2. σc is confining pressure, qmax is maximum applied axial stress, qcont is axial stress to keep positive contact between the cap and the specimen, qcyclic is cyclic applied axial stress, Nc is number of load cycles. As illustrated in Fig. 2, relative densities during whole MR test steps vary within one per cent, which are stable enough to prove the accuracy of measured resilient modulus.

Table 2. Testing sequence in MR test.

| Name  | σc  | qmax | qcont | qcyclic | Nc  |
|-------|-----|------|-------|---------|-----|
| MR-0  | 41.4| 27.6 | 2.76  | 24.84   | 2000|
| MR-1  | 41.4| 13.8 | 1.38  | 12.42   | 100 |
| MR-1.5| 41.4| 20.7 | 2.07  | 18.63   | 100 |
| MR-2  | 41.4| 27.6 | 2.76  | 24.84   | 100 |
| MR-2.5| 41.4| 34.5 | 3.45  | 31.05   | 100 |
| MR-3  | 41.4| 41.4 | 4.14  | 37.26   | 100 |
| MR-6  | 27.6| 13.8 | 1.38  | 12.42   | 100 |
| MR-6.5| 27.6| 20.7 | 2.07  | 18.65   | 100 |
| MR-7  | 27.6| 27.6 | 2.76  | 24.84   | 100 |
| MR-7.5| 27.6| 34.5 | 3.45  | 31.05   | 100 |
| MR-8  | 27.6| 41.4 | 4.14  | 37.26   | 100 |

Freeze-thaw unsaturated test applies freeze-thaw action before controlling matric suction. In other words, a freeze-thaw action is applied to a saturated specimen. Then, after the freeze-thaw process, the matric suction is controlled to make the specimen unsaturated. MR test will be started when the specimen reaches target degree of saturation.

Unfrozen unsaturated test is the simplest test through these three types of test. This method applying a determined matric suction value on the specimen and waiting for the equilibrium condition to get an unsaturated specimen. Then, MR test will be started directly.

![Fig. 2. Relative density during whole MR test steps.](image)

4 TEST RESULTS AND DISCUSSIONS

4.1 SWCC of Toyoura sand

Fig. 3 shows the soil–water characteristic curve for Toyoura sand (the relationship between matric suction (s) and volumetric water content (θ)) obtained from the present and previous study. The SWCC of this study is S-shaped with an inflection point where the matric suction increased as the volumetric water content decreased, and the shape qualitatively matches the results of previous studies (Ishikawa et al. 2014). In addition, to ensure the reliability of the uniform distribution of the water content inside a large unsaturated specimen, the water content (w) for the top, middle, and bottom of the specimen was examined after the water retentivity tests. The results show w=2.94%, 3.33%, and 4.25% for the top, middle, and bottom of the specimen, respectively. A uniform distribution of the water content is believed, though the water content in the top is slightly lower than bottom water content because pore air pressure and pore water pressure is applied on cap and pedestal respectively.

![Fig. 3. SWCC of Toyoura sand.](image)
Besides, the difference in SWCCs between a freeze-thawed specimen and an unfrozen specimen can hardly be recognized. Ishikawa et al. (2016) reports same observation and contributes this phenomenon to no particle breakage occurred due to freeze-thaw action, which led to little change in the water retentivity and permeability before and after freeze-thawing.

### 4.2 Effect of freeze-thaw on resilient modulus

Fig. 4 shows the volume of water drainage, axial displacement, the temperature of cap and pedestal during the freeze-thaw action. For an unsaturated specimen, the volume of water drainage varies around 0 ml during freeze-thaw process, which is quite different with a saturated specimen. A saturated specimen would drain about 25 ml water when it is frozen. This difference is quite reasonable because a 9% volumetric expansion of water will happen with the formation of ice and water will be squeezed out when the specimen is saturated. However, for an unsaturated specimen, as the existence of air voids, formation of ice may just occupy these voids. Another noticeable difference is axial displacement. Axial displacement of saturated specimen decreased about 1 mm when it is frozen, which equals to specimen height increased 1 mm. However, when the freeze-thaw action is applied to an unsaturated specimen, there is no increase of the specimen height. At the end of freeze-thaw, unsaturated specimen shows a little bit larger settlement, which causes a relatively higher density and lower void ratio. This difference may cause different mechanical properties.

Moreover, the resilient modulus of the freeze-thaw unsaturated specimen is the lowest among all tests results, which implies that a decreasing of resilient modulus caused by freeze-thaw is strongly related to the water content before frozen. More water contents exist in a specimen when the freeze-thaw action is applied, the resilient modulus decreases more significantly after a freeze-thaw action.

![Fig. 4. Volume of water drainage and axial displacement during freeze-thaw process.](image)

The resilient modulus of the unsaturated freeze-thawed specimen is shown in Fig. 5. It shows a good dependency of deviator stress and confining pressure. The resilient modulus decreases with larger deviator stress and smaller confining pressure.

As shown in Fig. 5, unfrozen unsaturated Toyoura sand shows higher resilient modulus. It is reasonable to conclude that, the freeze-thaw action decreases the resilient modulus even though the matric suction is kept as the same value before and after the freeze-thaw.

Moreover, the resilient modulus of the freeze-thaw unsaturated specimen is the lowest among all tests results, which implies that a decreasing of resilient modulus caused by freeze-thaw is strongly related to the water content before frozen. More water contents exist in a specimen when the freeze-thaw action is applied, the resilient modulus decreases more significantly after a freeze-thaw action.

![Fig. 5. Mr of unfrozen and freeze-thawed specimens.](image)

Mechanistic-Empirical Pavement Design Guide (American Association of State Highway and Transportation Officials 2008) proposed a universal model to predict the resilient modulus with stress variables as shown in Eq. (1).

\[
M_r = K_1 p_a \left( \frac{\theta}{\theta_a} \right)^{k_2} \left( \frac{\tau_{oct}}{\tau_{oct}^c} + 1 \right)^{k_3}
\]

where \( k_1, k_2, k_3, \) are regression constants; \( p_a \) is atmospheric pressure; \( \theta \) is bulk stress; \( \tau_{oct} \) is octahedral stress.

However, this model cannot reflect the effect of matric suction content. A modified universal model for unsaturated materials is used as shown in Eq. (2) (Ng et al. 2013). This model is based on the universal model with an additional term that incorporates matric suction effects into the resilient modulus. This model shows good applicability on predicting resilient modulus of unsaturated unbound materials through the relatively higher coefficient of determination (R²) than other models. Regression analysis for test results of resilient modulus is performed through this modified universal model to check the applicability. The regression analysis results are shown in Table 3 and Fig. 5.

\[
M_r = K_1 p_a \left( \frac{\theta}{\theta_a} \right)^{k_2} \left( \frac{\tau_{oct}}{\tau_{oct}^c} + 1 \right)^{k_3} \left( \frac{s_{net}}{s} + 1 \right)^{k_4}
\]

where \( k_1, k_2, k_3, k_4, \) are regression constants; \( p_a \) is atmospheric pressure; \( \theta \) is bulk stress; \( \tau_{oct} \) is octahedral stress; \( s_{net} \) is net normal stress; \( s \) is matric suction.

High coefficient of determination (R²) validates the applicability of the modified universal model. The modified universal model uses the regression constants \( k_2, k_3, \) and \( k_4 \) to reflect the influence of bulk stress, \( \theta \), octahedral shear stress, \( \tau_{oct} \), and matric suction, \( s \), on
resilient modulus separately. Since resilient modulus increases with larger bulk stress and matric suction, $k_2$ and $k_3$ are positive values. Besides, as resilient modulus decreases with larger octahedral shear stress, $k_1$ is a negative value. As a result, a larger absolute value of $k_2$, $k_3$, and $k_4$ means a higher effect of bulk stress, octahedral shear stress, and matric suction on resilient modulus. As shown in Table 3, $k_2$, $k_3$, and $k_4$ of the unsaturated freeze-thaw test have smaller absolute values comparing with them in the unfrozen unsaturated test, which implies that freeze-thaw also weaken the influence of bulk stress, octahedral shear stress, and matric suction. In other words, when the confining pressure or matric suction increase, the influence of bulk stress and octahedral shear stress would decrease more significantly.

Besides, when deviator stress increases a same value in both unfrozen unsaturated test and unsaturated freeze-thaw test, the resilient modulus of the unfrozen specimen would increase more significantly. Besides, when deviator stress increases a same value in both unfrozen unsaturated test and unsaturated freeze-thaw test, the resilient modulus of the unfrozen specimen would decrease more significantly.

Table 3. Regression analysis results.

| Test name                  | $k_1$   | $k_2$   | $k_3$   | $k_4$   | $R^2$  |
|----------------------------|---------|---------|---------|---------|--------|
| Unfrozen Unsaturated       | 40.161  | 0.853   | -0.432  | 3.397   | 0.978  |
| Unsaturated Freeze-thaw    | 46.542  | 0.800   | -0.404  | 2.934   | 0.974  |
| Freeze-thaw Unsaturated    | 47.817  | 0.637   | -0.258  | 21.759  | 0.987  |

For freeze-thaw unsaturated specimen, the effect of bulk stress and octahedral shear stress on resilient modulus is lowest through all three types of test, which is illustrated by the fact that the absolute value of $k_2$ and $k_3$ of the freeze-thaw unsaturated test are lowest in Table 3. As mentioned before, a lower absolute value of $k_2$ and $k_3$ illustrates a less significant effect of bulk stress and octahedral shear stress. The difference is that freeze-thaw action is applied to an unsaturated specimen or a saturated specimen. Regression analysis results of unsaturated freeze-thaw test and freeze-thaw unsaturated test illustrate that a freeze-thaw action applied on a saturated specimen deteriorates the influence of bulk stress and octahedral shear stress. It is reasonable to concludes that, the effect of freeze-thaw on the resilient modulus of Toyoura sand is strongly affected by the degree of saturation during freeze-thaw process. More water exists before freeze-thaw process, the loss of stiffness caused by the freeze-thaw becomes more significant.

As a result, a freeze-thaw process not only reduces resilient modulus greatly, but also weakens the influence of bulk stress, deviator stress, and matric suction on resilient modulus, even with same water content before and after freeze-thaw and these effects relates to the degree of saturation during freeze-thaw process.

4.3 Effect of freeze-thaw on other mechanical properties

Fig. 6 shows the permanent axial strain, $(e_a)_p$, and Secant Young’s modulus, $E_s$, in MR-0. The $(e_a)_p$ of the unsaturated freeze-thawed specimen is 0.01% at the end of MR-0, which is larger than that of the unfrozen specimen. The freeze-thaw unsaturated specimen shows the largest permanent axial strain. The permanent axial strain of unfrozen Toyoura sand is almost constant around zero. The Secant Young’s modulus in this research is defined as the amplitude of cyclic axial stress divided by the sum of permanent and resilient axial strain. It is noted that the unfrozen specimen shows a much higher Secant Young’s modulus value than those of the other two specimens. These differences illustrate that freeze-thawed Toyoura sand has worse mechanical properties. Moreover, freeze-thaw unsaturated specimen shows lowest secant Young’s modulus.

Consequently, freeze-thaw leads to a smaller Secant Young’s modulus and a larger permanent axial strain under repeated axial loads. It is suggested that the freeze-thaw process deteriorates the uniformity of particle skeleton structure and further leads to worse mechanical properties. Moreover, this deterioration is strongly related to the water content before applying freeze-thaw action. Because more water content exists before frozen, the deformation of specimen caused by formation of ice is more significant. Accordingly, the deterioration of the uniformity of particle skeleton structure are more obvious. As shown in Fig. 4, at the end of freeze-thaw, unsaturated specimen has a larger settlement than that of saturated one, which causes a relatively higher density and lower void ratio. Besides, saturated specimen height increased during the freeze-thaw process, but unsaturated specimen height did not. This difference also illustrates that saturated specimen suffered a more significant deterioration of the uniformity of particle skeleton structure. Therefore, unsaturated freeze-thaw specimen shows better mechanical properties than that of the freeze-thaw unsaturated specimen.

![Fig. 6. Permanent axial strain and Secant Young’s modulus in MR-0.](image-url)
which may be contradictory to the fact that unfrozen specimen has higher resilient modulus. In general, resilient modulus increases with increasing relative density when the specimen is homogeneous. This contradiction between relative density and resilient modulus may be due to a deterioration of the uniformity of particle skeleton structure caused by the freeze-thaw process. Formation of ice during the freezing process leads some parts of sample denser and other parts looser. Though these looser parts get denser again with thawing, which is illustrated by a decreasing of specimen height, the heterogeneousness still exists. As a result, freeze-thawed specimens have worse uniformity of particle skeleton structure though they show larger relative densities and this heterogeneousness of sample leads to a smaller resilient modulus and less sensitive to changing of bulk stress and deviator stress. However, this conclusion still needs more investigation about the changing details of particle skeleton structure before and after the freeze-thaw process.

5 CONCLUSIONS

The following findings can be mainly obtained:

- Test results show good consistency with previous research results like SWCC, which proves the validity of the test apparatus. Moreover, a test method for resilient modulus of unsaturated unbound granular materials subjected to freeze-thaw action is proposed and the most significant feature of this method is keeping matric suction stable during freeze-thaw action.
- A freeze-thaw process not only reduces resilient modulus greatly, but also weakens the influence of bulk stress, deviator stress, and matric suction on resilient modulus, even with the same water content before and after freeze-thaw.
- Besides resilient modulus, other mechanical properties like Secant Young’s modulus also deteriorates after freeze-thaw action. Freeze-thawed specimen also shows a larger permanent axial strain under repeated axial loads. However, as these findings are obtained through Toyoura sand with only one water content. Further and more comprehensive studies including more unbound granular materials with various water contents to further validate these findings are recommended.

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REFERENCES

1) American Association of State Highway and Transportation Officials (2003): Standard method of test for determining the resilient modulus of soils and aggregate materials (T 307-99), Standard specifications for transportation materials and methods of sampling and testing, ISBN 978-1-56051-710-8, American Association of State Highway and Transportation Officials, T 307, 1-42.

2) American Association of State Highway and Transportation Officials (2008): Mechanistic-empirical pavement design guide, A manual of practice, ISBN 978-1-56051-597-5, American Association of State Highway and Transportation Officials, 123-127.

3) Berg, R.L., Bigl, S.R., Stark, J.A., and Durell, G.D. (1996): Resilient modulus testing of materials from Mn/ROAD, Phase 1, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

4) Cole, D.M., Irwin, L.H., and Johnson, T.C. (1981): Effect of freezing and thawing on resilient modulus of a granular soil exhibiting nonlinear behavior, Transportation Research Record, 809, 19-26.

5) Ishikawa, T., Tokoro, T., Ito, K., & Miura, S. (2010): Testing methods for hydro-mechanical characteristics of unsaturated soils subjected to one-dimensional freeze-thaw action, Soils and Foundations, 50(3), 431-440.

6) Ishikawa, T., Kawabata, S., Kamayama, S., Abe, R. and Ono, T. (2012): Effects of freeze-thawing on mechanical behavior of granular base in cold regions, Proceedings of the 2nd International Conference on Transportation Geotechnics (ICTG), Sapporo, Japan, 118-124.

7) Ishikawa, T., Zhang, Y., Tokoro, T., & Miura, S. (2014): Medium-size triaxial apparatus for unsaturated granular subbase course materials, Soils and Foundations, 54(1), 67-80.

8) Japanese Geotechnical Society (2009): Test method for frost susceptibility of soils (JGS 0172-2009), Japanese Geotechnical Society Standards: Laboratory Testing Standards of Geomaterials (Vol. 2), ISBN 978-4-88644-083-9, Maruzen Print Co. Ltd., 230-258 (in Japanese).

9) Johnson, T.C., Cole, D.M., and Chamberlain, E.J. (1978): Influence of freezing and thawing on the resilient properties of a silt soil beneath an asphalt concrete pavement, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

10) Kishikawa, T., Ogtonjargal, D., Kawaguchi, T., Nakamura, D., and Yamashita, S. (2017): Influence of freeze-thaw on stress propagation in the ground. Proceedings of the 57th Technical Report of the Annual Meeting of the JGS Hokkaido Branch, Kitami, Japan, 27-34 (in Japanese).

11) Ng, C. W. W., Zhou, C., Yuan, Q., and Xu, J. (2013): Resilient modulus of unsaturated subgrade soil: experimental and theoretical investigations, Canadian Geotechnical Journal, 50(2), 223-232.

12) Seed, H.B., Chan, C.K., and Monismith, C.L. (1955): Effects of repeated loading on the strength and deformation of compacted clay, Proceedings of Highway Research Board Proceedings, Washington, United States, 34, 541-558.

13) Simonsen, E. and Isacsson, U. (2001): Soil behavior during freezing and thawing using variable and constant confining pressure triaxial tests, Canadian Geotechnical Journal, 38(4), 863-875.

14) Simonsen, E., Janoo, V.C., and Isacsson, U. (2002): Resilient properties of unbound road materials during seasonal frost conditions, Journal of Cold Regions Engineering, 16(1), 28-50.