Resilient properties of unbound granular materials subjected to freeze-thaw and wheel loads

Tianshu Lin[1], T. Ishikawa[2], R. Aoki[3], and T. Tokoro[4]

[1] Graduate School of Engineering, Hokkaido University, Kita 13, Nishi 8, Kita-Ku, Sapporo 0608628, Japan.
[2] Faculty of Public Policy, Hokkaido University, Kita 13, Nishi 8, Kita-Ku, Sapporo 0608628, Japan.
[3] Chiyoda Corporation, Minato Mirai Grand Central Tower 4-6-2, Nishi-Ku, Yokohama 2208765, Japan
[4] National Institute of Technology, Tomakomai College, 443, Nishikioka, Tomakomai 0591275, Japan.

ABSTRACT

This paper describes the result from resilient modulus tests of unfrozen, freeze-thawed, unfrozen-wheel loaded, freeze-thawed-wheel loaded, and frozen-wheel loaded-thawed soil, aiming to qualitatively and quantitatively estimate the effect of freeze-thaw and wheel loads on resilient properties. Freeze-thaw process not only reduces resilient modulus greatly, but also weaken the influence of bulk stress and deviator stress on resilient modulus. For unfrozen soil, wheel loads decrease the resilient modulus. For freeze-thawed soil, the wheel loads increase the influence of deviator stress on resilient modulus. Regression analysis with universal model displays good performance for all tests. However, the modified universal model used in enhanced integrated climatic model (EICM) does not show good applicability for freeze-thawed soil and the reason still need further investigation.

Keywords: resilient modulus; freeze-thaw; wheel loads

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. The M_r in cold regions like Hokkaido is strongly affected by the occurrence of seasonal frost, while most research aims 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. (1986), 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, the loss of stiffness is mainly attributed to the change of moisture. The effect of freeze-thaw has not been considered completely, which implies a requirement of further investigation. Wheel loads also show an effect on resilient properties. In this study, a series of MR tests were conducted to investigate the effect of freeze-thaw and wheel loads on M_r. The effect of degree of saturation, density, and temperature are not considered. This paper describes the result from MR tests of unfrozen, freeze-thawed, unfrozen-wheel loaded, freeze-thawed-wheel loaded, and frozen-wheel loaded-thawed soils, aiming to estimate the effect of freeze-thaw and wheel loads on resilient properties.

2 METHOD AND MATERIALS

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 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.

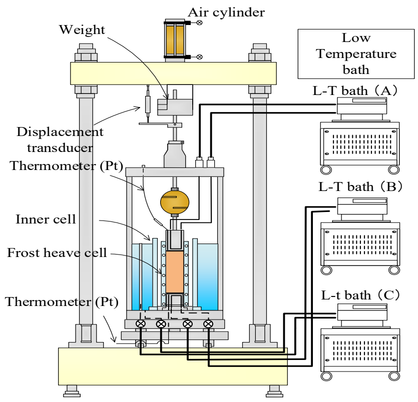

Fig. 1. Test apparatus.

2.2 Test materials

Toyoura sand was used as test materials. Specimens were prepared by air pluviation method and the degree of compaction (D_c) was 96% and dry density (ρ_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 same to the highest confining pressure in the MR test (AASHTO 2003).

2.3 Test method

This study conducted unfrozen test (U test), unfrozen-wheel loads test (UW test), freeze-thaw test (FT test), freeze-thaw-wheel loads test (FTW test), and frozen-wheel loads-thawed test (FWT test). The wheel loads were q_{cont}=9.6 kPa, q_{cyclic}=24.5 kPa in winter and 26.2 kPa in spring, which were calculated by the General Analysis of Multi-layered Elastic Systems (GAMES) (Maina and Matsuki 2004). Subscript "$_{cont}$" means a constant axial load to simulate the overburden pressure caused by surfacing layer, base course and subbase. Subscript "$_{cyclic}$" stands for applied cyclic axial stress to simulate wheel loads. Details of test condition are shown in Table 1. MR tests were performed according to AASHTO T307-99 (AASHTO 2003). A haversine wave load pulse with a frequency of 0.2 Hz was applied due to the limitation of the apparatus. 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 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. σ_c is confining pressure, q_{max} is maximum applied axial stress, q_{cont} is axial stress to keep positive contact between the cap and the specimen, q_{cyclic} is cyclic applied axial stress, N_c is number of load cycles.

Fig. 2 shows the temperature, displacement, and volume of water drainage during freeze-thaw process in the FTW test. To achieve one-dimensional freeze-thaw, the initial temperature of cap and pedestal were set to 0ºC and 16.8ºC 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 as 16.8ºC. Then, the temperature of cap and pedestal were lowered to -18.9ºC and -2.1ºC respectively with a constant cooling rate of 1.67ºC/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 5ºC and 16.8ºC with a heating rate of 1.67ºC/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.

Table 1. Test condition.

Name	Test sequence	
U	Unfrozen →	MR test
UW	Unfrozen → Wheel loads →	
FT	Freeze-thaw →	
FTW	Freeze-thaw → Wheel loads →	
FWT	Frozen → Wheel loads → Thaw →	

Table 2. Testing sequence in resilient modulus test.

Name	σ_c (kPa)	q_{max} (kPa)	q_{cont} (kPa)	q_{cyclic} (kPa)	N_c
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	18.63	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

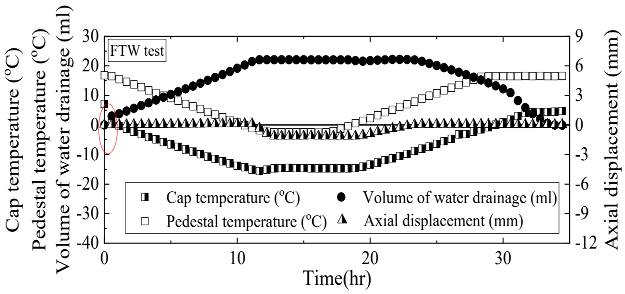

Fig. 2. Freeze-thaw process.

3 DATA ANALYSIS

M_r is the ratio of the amplitude of cyclic axial stress to the amplitude of the resultant recoverable axial strain. Based on MR test results, nonlinear regression analyses were performed with universal model (AASHTO 2008) by Eq. (1) and EICM (NCHRP 2004) by Eq. (2) to check their applicability. The only difference between two models is the EICM using a factor, F_{env}, to represent the reduction of M_r due to freeze-thaw. F_{env} is a reduction factor that equals to the M_r of freeze-thawed soil divided by M_r of unfrozen soil.

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

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

where k_1, k_2, k_3 are regression constants; p_a is atmospheric pressure; θ is bulk stress; τ_{oct} is octahedral stress; F_{env} is composite environmental adjusting factor.

4 RESULTS AND DISCUSSION

4.1 Effects on resilient modulus

Fig. 3(a) shows the M_r of U test and UW test. Fig.

3(b) shows the M_r of FT test, FTW test, and FWT test. M_r of unfrozen toyoura sand shows a good dependency on deviator stress, q, and confining pressure, σ_c. To be specific, the M_r decreases with increasing q or decreasing σ_c. Because a lower σ_c leads to a reduction of frictional force, which in turn leads to a decline in resisting soil deformation. UW test shows a lower M_r though influence of q and σ_c on M_r are still significant.

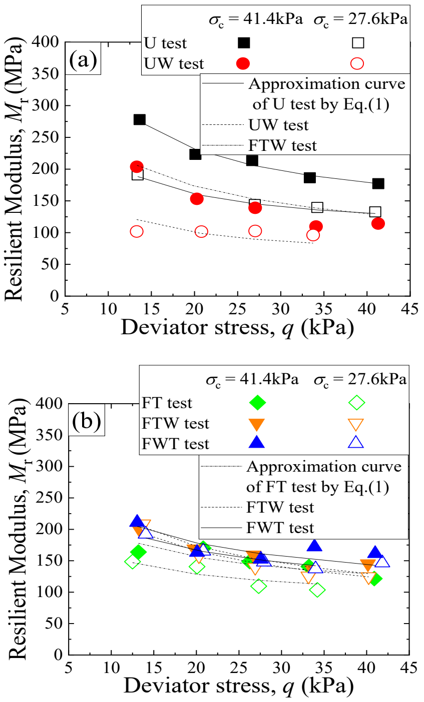

Fig.3. M_r of U, UW, FT, and FTW tests.

Comparing FT test and U test, the freeze-thaw greatly lowers M_r. Meanwhile, the influence of q and σ_c on M_r are much less significant in FT test than in U test. Through comparing UW test and FTW test, the influence of σ_c on M_r is much lower in FTW. It is suggested that freeze-thaw process deteriorated the uniformity of particle skeleton structure and further led to a lower M_r and a less significant influence of q and σ_c on M_r. As the effect of moisture content on M_r is removed through keeping specimen fully-saturated before and after freeze-thaw. Through comparing the results of FT test and FTW test, the wheel loads after freeze-thaw process elevate M_r a little. Because the role of wheel loads for freeze-thawed soil is some kind of a consolidation to help specimen regain the uniformity of particle skeleton structure. M_r of FWT test is also at low level and the influence of q and σ_c are also much less significant than in U test. The similarity between FWT and FT, FTW test results implies that the traffic wheel loads applied on frozen specimen does not affect M_r greatly.

4.2 Effects on plastic deformation

Fig. 4 shows the permanent axial strain, $(\varepsilon_a)_p$, in MR-0. The $(\varepsilon_a)_p$ in UW and FTW tests are almost constant around zero because the wheel load process with greater axial stress were conducted prior to MR-0. The $(\varepsilon_a)_p$ in FT test is smaller than U test before 1300 cycles, and then increases to a similar level. As the height of specimen and degree of saturation did not change greatly before and after freeze-thaw. It is reasonable to suggest that the freeze-thaw process deteriorated the uniformity of particle skeleton structure and further led to a lower $(\varepsilon_a)_p$ at initial period. The $(\varepsilon_a)_p$ in FWT test is around zero before 600 cycles, then increases to a similar level with FT test results. At the end of MR-0, The $(\varepsilon_a)_p$ in FWT test is a little bit smaller than that in FT test.

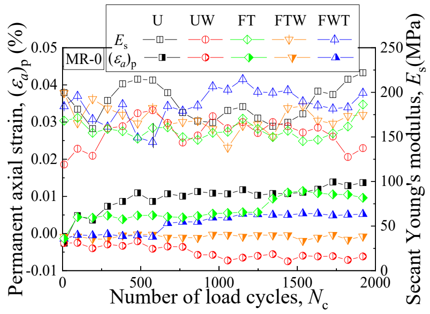

Fig. 4. Residual strain and secant Young's modulus in MR-0.

Fig. 4 also shows the secant Young's modulus, E_s, in MR-0. The E_s in this research is defined as the amplitude of cyclic axial stress divided by total strain. U test shows the highest E_s and UW shows the lowest value, which illustrates that wheel loads lead to a reduction of E_s for unfrozen soil. Whereas, FT, FWT and FTW have similar value, which implies that the wheel loads have no apparent effect on E_s for frozen and thawed soil.

4.3 Applicability of universal model and EICM

Universal model uses the regression constants k_2 and k_3 reflect the influence of bulk stress, θ, and octahedral shear stress, τ_{oct}, on M_r separately. Because M_r increases with increasing θ and decreases with increasing τ_{oct}, k_2 is a positive value and k_3 is a negative value. A larger absolute value of k_2 or k_3 means a higher effect of θ or τ_{oct} on M_r. Mechanistic-Empirical Pavement Design Guide (MEPDG) also uses EICM to predict resilient modulus for unbound pavement materials exposed from the environmental action as shown in Eq. (2).

Table 3 and Fig. 3 show the results of regression analysis with universal model. Universal model shows good applicability for U test, UW test, and FTW test. Only FT and FWT test shows a coefficient of determination (R^2) around 0.8, all other tests show a R^2 close to or higher than 0.9. As the precision of axial displacement transducer is 0.01 mm in this study, it is possible that some experimental errors existed and, thus caused such a lower R^2. Comparing regression constants in U test and UW test, k_2 and k_3 in both tests are almost similar, which implies a similar influence of θ and τ_{oct} on M_r. Therefore, it is reasonable to indicate that wheel loads for unfrozen soil decreases the M_r but keeps the dependency of stress on M_r. Whereas, FT test shows a lower absolute value of k_2 and k_3 than U test regression results, which illustrates a less significant influence of θ and τ_{oct} on M_r. It should be noticed that the comparison of regression constants between U test and FT test could only be treated as a complement to Fig. 3 because the R^2 of FT test is low. Furthermore, FTW shows a smaller k_2 and a larger absolute value of k_3 than FT test regression results. These results indicate that wheel loads for freeze-thawed soil leads to a lower effect of θ and a higher effect of τ_{oct} on M_r. FWT has similar k_3 and lower k_2 compare with that of FT, implies the traffic wheel loads applied on frozen soil decreases the effect of θ. We calculate the average reduction rate of M_r when deviator stress is same but confining pressure decreases from 41.4 kPa to 27.6 kPa. M_r in U test, UW test, FT test, FTW, and FWT test decreased 29.1%, 30.6%, 19.8%, 5.36%, and 8.04% respectively. U test and UW test display highest reduction rate and FTW test shows lowest reduction rate. This is consistent with previous observation.

Table 3. Regression analysis results.

Name	k_1	k_2	k_3	F_{env}	R^2
U test	19.117	1.080	-0.577	-	0.988
UW test	3.605	1.325	-0.673	-	0.897
FT test	178.996	0.574	-0.381	-	0.795
FTW test	6566.333	0.139	-0.445	-	0.900
FWT test	2672.367	0.200	-0.350	-	0.817
FT test (with EICM)	19.117	1.080	-0.577	0.707	0.404

In EICM, the reduction of M_r due to freeze-thaw process is estimated by an adjustment factor, F_{env}, and other regression constants in EICM model, k_1, k_2 and k_3, are determined by regression constants of unfrozen soil obtained by universal model. In another word, regression analysis for U test with universal model and FT test with EICM model share same k_1, k_2 and k_3. Regression results for FT test with these two models are shown in Table 3. The R^2 of EICM is much lower than the result of universal model. The influence of confining pressure and deviator stress on M_r for freeze-thawed soil is less significant than that of unfrozen soil. In this situation, same k_2 and k_3 will decrease the applicability of EICM. However, further research is required to verify these observations.

5 CONCLUSIONS

- Test results show good consistence with results of previous research and prove the validity of the test apparatus.
- Freeze-thaw process not only reduces resilient modulus greatly, but also weaken the influence of bulk stress and deviator stress on resilient modulus. The reduction of resilient modulus for freeze-thawed soils due to increasing deviator or decreasing confining pressure is less significant than for unfrozen soils.
- Effect of wheel loads on resilient modulus of unfrozen soils and freeze-thawed soils are different. For unfrozen soil, wheel loads decrease the resilient modulus. For freeze-thawed soil, the wheel loads increase the influence of deviator stress on resilient modulus.
- Regression analysis with universal model displays good performance for all tests. However, the modified universal model used in EICM does not show good applicability for freeze-thawed soil and the reason still need further investigation.

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REFERENCES

AASHTO (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, Washington, T 307, 1-42.

AASHTO (2008). Mechanistic-empirical pavement design guide, A manual of practice, Washington.

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.

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.

Japanese Geotechnical Society (2009). Test method for frost susceptibility of soils (JGS 0172-2009). Standards of Japanese Geotechnical Society for Laboratory Soil Testing Methods, Tokyo, 45-50. (in Japanese)

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.

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

Maina, J. and Matsui, K. (2004). Developing software for elastic analysis of pavement structure responses to vertical and horizontal surface loadings. Journal of the Transportation Research Board, 1896, 107-118.

NCHRP (2004). Guide for mechanistic-empirical design of new and rehabilitated pavement structures. National Cooperative Highway Research Program 1-37 A.

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

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.

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.