Applicability of unsaturated soil mechanics for resilient modulus: Case study of a Korean experience

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ABSTRACT

In 2004, the KHC test road was constructed to evaluate long-term performance of the pavement under actual road environment in Korea, and pavement responses were monitored. To consider a mechanical behaviors of foundation materials, the resilient modulus was adopted for the subbase and subgrade layer instead of CBR. Therefore, a need exists that the resilient modulus should combine the effects on mechanical and environmental loadings reasonably. For this, stress-and moisture-dependent nonlinear resilient modulus model is introduced using unsaturated soil mechanics approach. Then the proposed model was evaluated based on the various laboratory tests based on KHC test road conditions. Some of these efforts are illustrated in this paper by a combination of field observations from a Korean experience on KHC test roads and estimation made by stress and moisture-dependent analyses guided by theory which explains the suction stress.

Keywords: KHC test road; resilient modulus; suction stress; pavement design

1 INTRODUCTION

As an important input parameter for mechanistic-empirical pavement design of the road, resilience modulus for base and subgrade has been introduced since 1986 from AASHTO based on a concept of resilient strains under the repeated traffic loading condition. In general mechanical response of pavement foundations is influenced by various factors such as water content, density, particle size, and stress intensity. Among them, the water content is the main factor affecting the mechanical behavior of road and change in water content can decrease the magnitude of the resilient modulus at 50% for full saturated condition (Li & Qubain 2003).

Since resilient modulus concept was adopted back in 1980s for pavement design, many approaches and methods are introduced empirically for considering these water effects, however, there is no sound and reasonable ME models.

Recently, theoretical and experimental approach for an effective stress in unsaturated state soils has been progressed and made promising results. suction stress is a stress state variable established in unsaturated soil mechanics and is known as a factor that can express unsaturated stress. Therefore, it is necessary to apply the suction stress in the model for resilient modulus for the water content or degree of saturation variation. In this paper, field and laboratory behaviors on pavement foundations will be illustrated based on KHC test roads in Korea and modulus model using suction stress is presented as well.

2 KHC TEST ROAD

Korea Highway Corporation test road was built to evaluate the long-term performance of road pavement and to analyze the behavior of the pavement response by traffic loadings and speed, and some of environmental measures (In et al. 2006). The pavement on the test road has various section components and optimal conditions for analyzing the behavior of the pavement. The result of the test road used part of the development of Korean mechanical–empirical pavement design guide.

The test road of asphalt pavement is composed of 33 sections in 2.7km with the base, subbase and anti-frost layer to understand mechanical behavior characteristics of the road. The basic physical properties of the ground material of the test road are as shown in Table 1. Part of the test results are illustrated as shown in below.

The earth pressures were measured under the static load of 689kPa in September and November 2004, August 2005, and April 2006 in A5, and A14 sections, and the strain data was analyzed at September and November 2004. The earth pressure equipment is located at the lower part of the middle, base, and subbase layer. The strain gage is embedded in the asphalt-stabilized layer and the lower middle layer. The thickness of the base layer of A5 and A14 is 18cm, and it is possible to analyze the results according to the base material, base layer thickness and seasonal change through two sections.

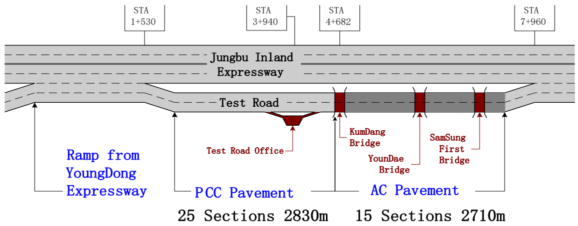
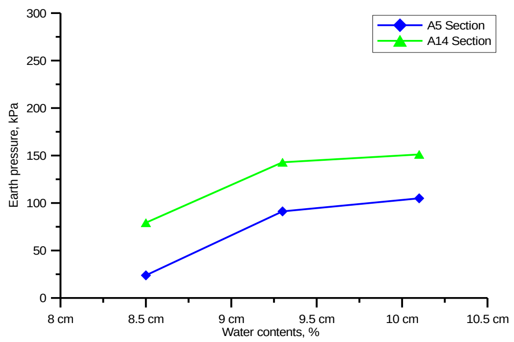


Fig. 1. The pavement section configuration and measurement Location (Kim et al. 2003)

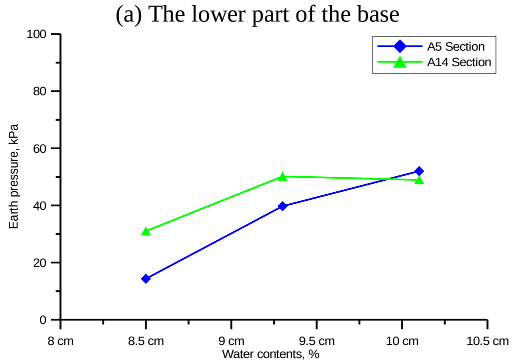
Table 1. Properties of the ground material under test road

	Subbase	Subgrade
Soil classification, USCS	GW	SW
Specific gravity	2.717	2.653
Passing sieve #200(%)	3.38	4.92
Optimum water content(%)	5.51	9.42
Max. dry unit weight (kN/m3)	21.58	18.86

The earth pressure is measured at the lower part of the base layer and the lower part of the subbase layer, and the earth pressure changes according to the water content change. As the water content increases, the earth pressure tends to increase, so the water content in the ground affects the earth pressure.



(a) The lower part of the base



(b) The lower part of subbase

Fig. 2. Distribution of earth pressure according to the change of water content.

By comparing the tensile strain of the under-layer asphalt, the tensile strain measured in September is larger than that of November, which is relatively smaller water content condition. Therefore, change in layer water content has a significant effect on not only the earth pressure but also the tensile strain of the ground based on field measurements. So, a need exists that the resilient modulus of the layer soils should be evaluated considering both mechanical and moisture behaviors for making an accurate evaluation.

3 MODULUS AND SUCTION STRESS

Resilient modulus models are proposed by past many studies. Among them, an empirically deriven expression is well known in AASHTO MEPDG module, and some are modified like by Liang et al. (2008) and Khoury et al. (2009). The degree of saturation, or water content, and matric suction is adopted in those models.

While Karube and Kato (1994) firstly proposed a conception of 'Meniscus water' and 'Bulk water' for stress state condition of unsaturated soils. Bulk water is the pore water which occupies the pore volume between soil particles, and meniscus water exists at the contact point between soil particles. The proportion of bulk water in the soil water increases with the degree of saturation. On the contrary, the proportion of meniscus water increases with a decrease in the degree of saturation. Therefore, it is necessary to examine the influences of the bulk water and the meniscus water on the soil skeleton to consider the mechanical behaviors of unsaturated soils.

Karube et al. (1996) presumed the proportion of the pore water by the driest curve because it is impossible to distinguish the proportion of the pore water such as meniscus and bulk water in reality. Thus, by considering the quantity of the soil water related to the driest curve which is a wetting path under assumptive pore water distribution, only the meniscus water exists at contact points until the entire void of soils fills with the pore water, while the bulk water does not exist.

From such an assumption, they defined the stress components caused by the influence of meniscus water and bulk water as the meniscus stress (P_m) and the bulk stress (P_b), respectively. The suction stress can be defined as the summation of two stress components. Furthermore, the suction stress (P_s) in terms of the relation of matric suction (s) can be defined with the relation between the degree of saturation (S_r) and the residual degree of saturation (S_{r0}) through the relation of the driest curve as shown in Eq. (1).

$$P_s = P_m + P_b = \frac{S_r - S_{r0}}{100 - S_{r0}} \cdot s \qquad \text{Eq. (1)}$$

Where, P_s is the suction stress; P_m is the meniscus stress; P_b is the bulk stress; S_r is the degree of saturation; and S_{r0} is the residual degree of saturation. Therefore, it is possible to apply the influence of water content and suction in the ground through suction stress such as stress, which is very consistent and reasonable in estimating the resilient modulus. Eq. (2) is extended by applying the suction stress proved in the shear strength section, so it is considered that predicting the resilient modulus is more applicable.

$$M_R = k_1 P_a \left(\frac{\theta_b + 3P_s}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a}\right)^{k_3} \qquad \text{Eq. (2)}$$

Where M_R is the resilient modulus; θ_b is the bulk stress ($\theta_b = \sigma_1 + \sigma_2 + \sigma_3$); P_s is the suction stress; τ_{oct} is the octahedral shear stress($\tau_{oct} = \frac{\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}}{3}$); P_a is the atmosphere pressure; and k_1, k_2, k_3 is the model parameters..

4 MATERIAL

To validate the proposed resilient modulus model, tests were carried out on the subbase and base subgrade layer on the test road. The property of the materials is shown in Table 1. The universal testing machine, UTM-25, was used for accusing the resilient modulus. The diameter of the specimen was 100 mm, height 150 mm, and the specimen was molded using a gyratory compactor, which uses the principle of shear compaction. Since the annual variation of the water content of the test roads was +2% or -2% based on the optimum water content, samples were made at + 2%, OMC, and -2% based on field monitored data from KHC test roads.

The load conditions were tested using the TP46-94 specification of AASHTO, and the cyclic load was applied with a Haversine waveform with a rest period of 0.9 sec. after a load of 0.1 sec. per cycle. The test was performed at 100cycles per load combination. Besides, the soil-water characteristic test was performed to estimate the suction stress for the unsaturated soil, and the soil-water characteristic test was acquired from the pressure plate test.

5 COMPARISON OF MODULUS

The resilient modulus obtained from the test and predicted resilient modulus with the suction stress of the subbase at the same density and water content (OMC) is shown in Fig. 3(a). The resilient modulus increases as the confining pressure increases. When the suction stress is applied, the behavior due to the deviator stress and confining stress does not show much difference from acquiring the resilient modulus in the figure. As shown in Fig. 3(b), the resilient modulus increases as the confining pressure increases and the resilient modulus estimated by the model with suction stress are not significantly different from the measured modulus. Therefore, it can be concluded that the proposed model can estimate the resilient modulus for the stress distribution in the subbase layer and the base layer.

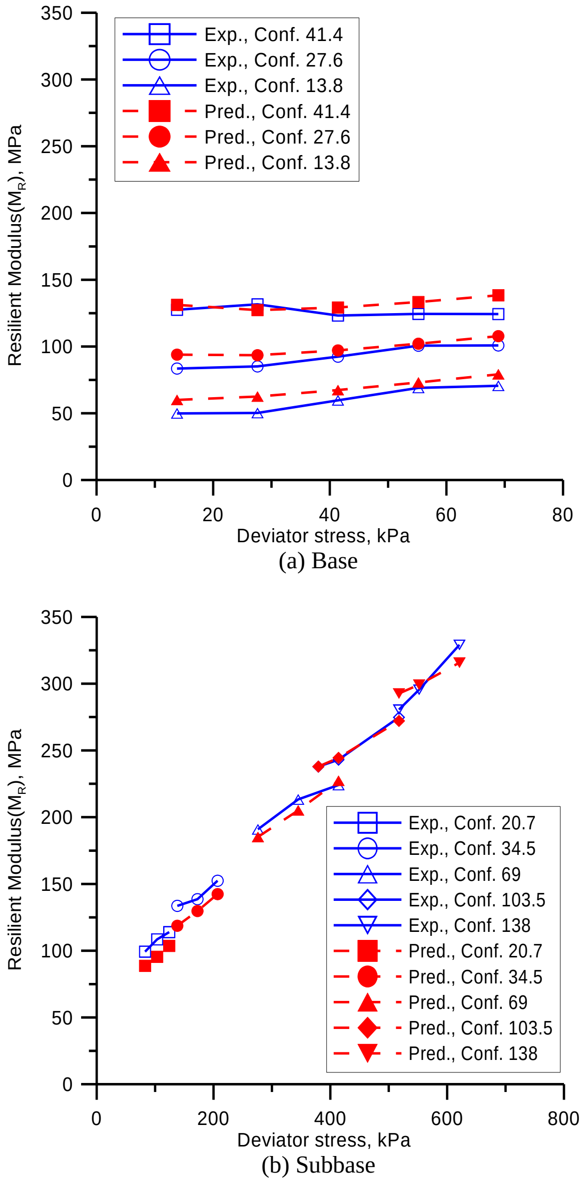
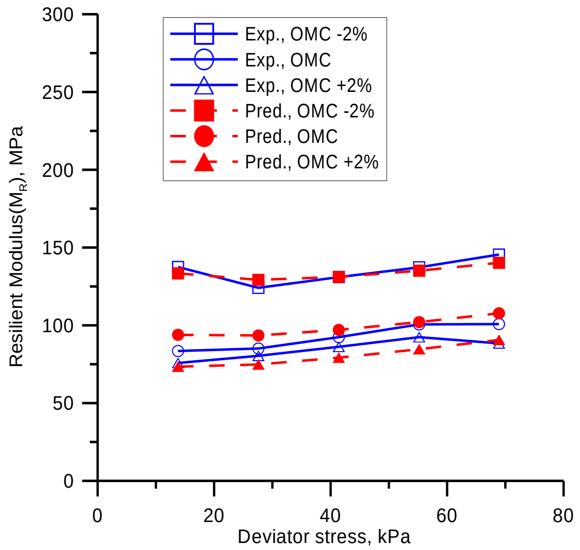


Figure 3. Comparison between measured and predicted modulus with respect to confining pressures

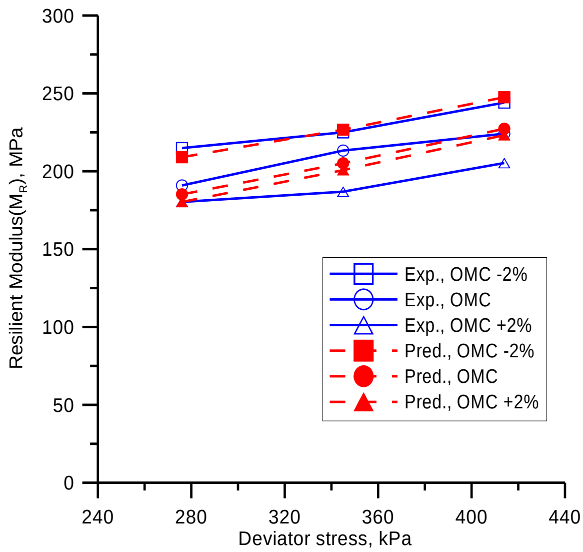
The resilient modulus calculated from the test when the density and stress conditions are the same, and the water content is only changed as Fig. 4. Fig. 4(a) shows the data when deviator stress of 27.6kPa is applied and Fig. 4(b) shows the data when the confining pressure of 69kPa is applied. As shown in Fig. 4, the resilient modulus decreases as the water content increases and the behavior of confining pressure is the same under different stress conditions. Also the resilient modulus estimated by applying the suction stress shows that the resilient modulus increases as the water content increases as the test results show and the difference from the actual measured value is not significant.

Therefore, since the increase of the suction stress is relatively small as the degree of saturation increases, it is considered that there is a difference. However, the error rate is about 4.5% in the case of the base and 6.2%

in the case of the subbase. On the other hand, when applying the proposed model in MEPDG, the error rate is about 2.7% in the case of the base and 10.3% in the case of the subbase. Therefore, it is possible to estimate the resilient modulus of the base and subbase layer according to the water content change through the model adopted the suction stress.



(a) Base



(b) Subbase

Figure 4. Comparison between measured and predicted modulus with respect to moisture conditions

6 CONCLUSION

The subjects covered in this paper show many of the most important variables and material properties that are needed to make an accurate evaluation for layered foundations under traffic loadings. And the field, laboratory and foundation response are illustrated based on the Korea Highway Corporation test road. The following conclusions are as below.

1. Models with suction stress exhibit the same behavior as the test data carried out on the base and subbase materials with changes in the resilient modulus depending on the various stress conditions. Therefore, it is very reasonable to apply the model with the suction stress.
2. The resilient modulus increases with decreasing water content and the same resilient modulus predicted by the model using suction stress. Since the error rate between the model and the experimental data is relatively low, the extended model can estimate the resilient modulus through changing the water content.

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