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Influence of Post Compaction on the Moisture Sensitive Resilient Modulus of Unbound Granular Materials

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Abstract

The impact of moisture on the resilient modulus (M_R) of unbound granular materials (UGMs) was investigated based on repeated load triaxial (RLT) tests and considering the effect of post compaction (PC) from cyclic loading. Results showed that although M_R decreases with increased moisture, it may appear to increase with increased moisture if the PC process is aided by moisture for a relatively large number of load applications. When limited PC was involved, the parameter k_1 of the k-θ model decreased with increased moisture while the parameter k_2 was unaffected. On the other hand, when significant amount of PC took place, k_2 increased with increased moisture. The mechanistic-empirical pavement design guide (MEPDG) model worked well to capture the influence of moisture on the stiffness when M_R decreased with increased moisture. However, it did not work when M_R increased with increased moisture due to the PC effect. On the other hand, an alternative approach expressing k_1 and k_2 as functions of moisture worked well for both situations. Generally, this study suggested that the effect of PC should be considered in modelling the impact of moisture on M_R for better accuracy.

Keywords: unbound granular materials, resilient modulus, moisture, post compaction, repeated-load triaxial test, modelling

1 Introduction

The moving heavy traffic loads on flexible pavements induce cyclic stresses on the unbound granular materials (UGMs) of the base and sub-base layers. The total deformation of UGMs under cyclic loading consists of resilient or recoverable deformation (RD) and plastic or permanent deformation (PD). The RD of the UGMs is often associated with the fatigue cracking in the asphalt concrete layer. The resistance against RD of UGMs is characterized using the resilient stiffness or resilient modulus (M_R). Among several other factors, M_R of UGMs is significantly influenced by moisture (Lekarp 1999, Ekblad

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2007, Erlingsson 2010, Cary and Zapata 2011, Rahman and Erlingsson 2013). Thus proper modelling of the variation of M_R of UGMs with seasonal variation of moisture is essential for analytical design of flexible pavements.

The objective of this study was to investigate the influence of post compaction (PC) and associated PD due to cyclic loading on the moisture sensitivity of the stiffness characteristics of UGMs. The RD behavior of a typical UGM used in pavement construction was studied using the Repeated-Load Triaxial (RLT) test. The RLT tests were carried out for a range of moisture contents (w) in two phases. In one phase the tests were performed using relatively small number of load cycles inducing negligible PC. In the other phase relatively larger number of load cycles was applied resulting in significant amount of PC. The results were then compared and modelled for both phases.

2 Deformation Characteristics of UGMs

The RD and PD in UGMs are non-linear stress dependent (Kolisoja 1997, Lekarp 1999, Uthus 2007, Englund 2011, Rahman 2015). These are influenced by several factors such as stress history, grain size distribution, moisture content and degree of compaction.

The M_R is dependent on the state of stress, measured as the sum of the principal stresses, called the bulk stress, $\theta = \sigma_1 + \sigma_2 + \sigma_3$. The variation of the M_R with θ can be expressed with the well-known k-θ model (Seed et al. 1962, Hicks and Monismith 1971, Uzan 1985) in its dimensionless form:

$$M_R = k_1 p_a \left(\frac{\theta}{p_a} \right)^{k_2} \tag{1}$$

where k_1 and k_2 are material parameters and p_a = 100 kPa (the atmospheric pressure).

The M_R of UGMs is mostly reported to decrease with the increase in w (Lekarp 1999, Li and Baus 2005, Ekblad 2007, Uthus 2007, Erlingsson 2010, Bilodeau and Doré 2011, Salour and Erlingsson 2013, Saevarsdottir and Erlingsson 2013). Some opposite trend was reported by Richter and Schwartz (2003) based on falling weight deflectometer (FWD) measurements during the long term pavement performance (LTPP) seasonal monitoring program as well as by Thom (1988) and Dawson et al. (1996). Above the optimum moisture content (w_{opt}), with increased degrees of saturation (S), the M_R is generally reported to decrease significantly (Dawson et al. 1996, Kolisoja 1997, Lekarp 1999).

The current Mechanistic Empirical Pavement Design Guide (MEPDG) by AASHTO (The American Association of State Highway and Transportation Officials) uses the following model to characterize the effect of moisture on the M_R (ARA 2004):

$$\log_{10} \frac{M_R}{M_{Ropt}} = a + \frac{b-a}{1 + EXP\left(\ln \frac{-b}{a} + k_m \left(S - S_{opt}\right)\right)} \tag{2}$$

where, M_{Ropt} = resilient modulus at optimum moisture content (w_{opt}), a=minimum of log (M_R/M_{Ropt}), b=maximum of log (M_R/M_{Ropt}), k_m=regression parameter dependent on material properties, S=degree of saturation expressed as decimal, and S_{opt}=degree of saturation at w_{opt} expressed as decimal.

PD in UGMs accumulates with the number of load applications. Based on the shakedown theory, Dawson and Wellner (1999) and Werkmeister et al. (2001) have identified that the accumulation of the PD in UGMs falls within the three shakedown ranges depending on stress levels (Figure 1). Range A occurs for relatively low stress levels when permanent strain accumulates up to a finite number of load applications after which the response becomes entirely resilient with no further permanent strain. For stress levels higher than this, Range B occurs where the accumulation of permanent strain continues at a constant rate (per cycle). When stress levels are even higher, Range C behavior is observed where the permanent strain accumulates at an increasing rate that may eventually lead to failure.

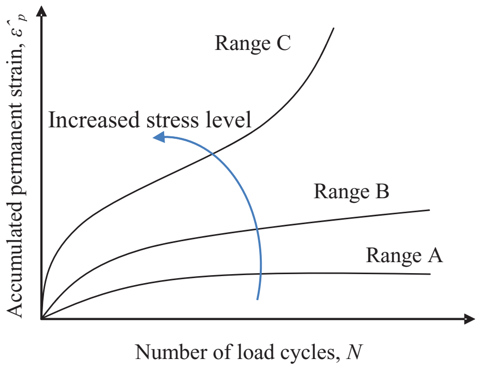

Figure 1: Different types of PD behavior, depending on stress level

For RLT tests, the boundaries of the different shakedown ranges may be defined using the following criteria (Werkmeister 2003, CEN 2004a):

$$
\begin{aligned}
&\text{Range A: } (\hat{\varepsilon}_p^{5000} - \hat{\varepsilon}_p^{3000}) < 0.045\times10^{-3} \\
&\text{Range B: } 0.045\times10^{-3} < (\hat{\varepsilon}_p^{5000} - \hat{\varepsilon}_p^{3000}) < 0.4\times10^{-3} \\
&\text{Range C: } (\hat{\varepsilon}_p^{5000} - \hat{\varepsilon}_p^{3000}) > 0.4\times10^{-3}
\end{aligned}
\tag{3}
$$

where $\hat{\varepsilon}_p^{3000}$ and $\hat{\varepsilon}_p^{5000}$ are accumulated permanent strains at 3000th and 5000th load cycles, respectively, in the RLT test.

3 Experimental Investigation

In this study, the RLT tests were carried out in accordance with the European standard EN-13286-7 (CEN 2004a). Identical cylindrical specimens of 150 mm in diameter and 300 mm in height with a range of moisture contents were tested. To investigate the impact of moisture on the RD behavior without any significant amount of accompanying PD, the resilient modulus test was carried out at a constant confining pressure using high stress level (HSL) from the standard. In this case a relatively low number of load cycles (2,900 in total for the 29 stress paths) are applied that results in negligible amount PD and PC. On the other hand, the impact of PD and PC on the moisture sensitivity of M_R was investigated by performing the PD test with the multi-stage (MS) loading approach from the same standard. The total number of load cycles for the PD tests with the HSL and the low stress level (LSL) are 280,000 (28 stress paths) and 300,000 (30 stress paths), respectively. It should be noted here that for each test the bulk stress level varied with the application of several stress paths to a specimen. Further details of the RLT test setup can be found in Rahman (2015).

The UGM used for this study was a crushed rock aggregate (granite) commonly used in pavement construction in Sweden. The grain size distribution was derived using Fuller's equation with grading coefficient n = 0.35 with the maximum particle size of 31.5 mm and 12% fines content (<75μm). Relatively finer grain size distribution was selected for this study in order to obtain a more pronounced effect of moisture. The optimum moisture content (w_{opt} = 6.5%) and the maximum dry density (2.22 gm/cc) were determined using the modified Proctor method according to European standard EN 13286-2 (CEN 2004b). Here the moisture contents of the specimens were reported as the degree of saturation (S). The results presented here are based on two replicates of each RLT test.

4 Results

4.1 M_R from the Resilient Deformation Tests

The M_R values obtained from the RD tests, plotted against θ for each S in Figure 2(a), shows that the M_R dropped gradually with increased S for the whole range of θ. The k-θ model was fitted to the data for each S and the parameters k_1 and k_2 were plotted against S in Figure 2(b). It is seen that k_1 decreased with increasing S while k_2 was fairly unaffected by moisture. An exponential function was fitted through the $k_1$versus S plots for which the following expression of the k-θ model can be obtained that may be used for computing the variation of M_R with S:

$$M_R = a_1 e^{-a_2 S} p_a \left(\frac{\theta}{p_a}\right)^{k_2} \tag{4}$$

where a_1 and a_2 are material parameters. This expression along with the MEPDG model stated in Equation 2 was used to capture the variation of M_R (for θ=550 kPa) with S, shown in Figure 3. Visual observation and the coefficient of determination (R^2) values in Figure 3 suggest that good qualities of fits were obtained with both the models.

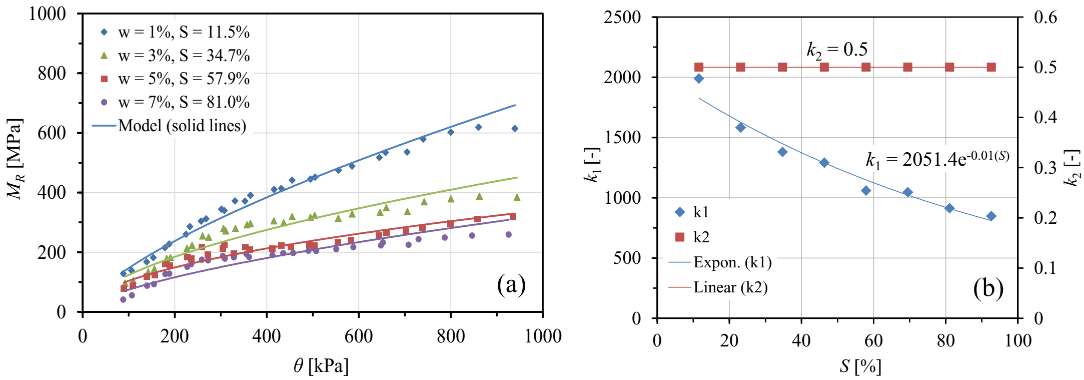

Figure 2: RD tests: (a) M_R as a function of θ for various w and S, (b) k_1 and k_2 as a function of S

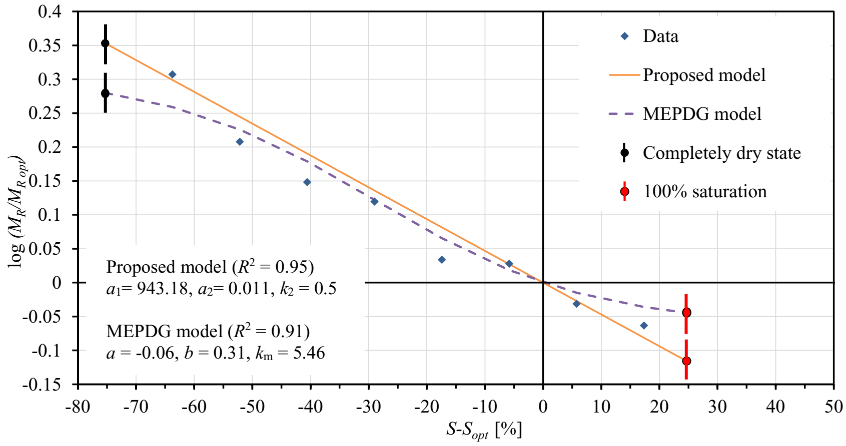

Figure 3: Normalized M_R as a function of change in S (for θ = 550 kPa): modelled vs. measured (RD tests)

4.2 M_R from the Permanent Deformation Tests

The M_R values obtained from the PD tests are plotted against θ for different ws in Figure 4(a). The results show some difference compared to the RD tests as the M_R values (and the trend lines) for the different ws are seen to cross each other. The M_R decreased with increased w in the early stage of the tests for relatively lower θ values (corresponding to lower N and lower accumulated PD). But at the later stages of the tests, for higher θ values (corresponding to higher N and higher accumulated PD), the trend was quite the opposite. In this case, the M_R was found to increase with θ at a faster rate (steeper slope of the M_R versus θ curves) for the higher ws. This resulted in a higher value of the M_R for the specimens with higher w at the later stages of the tests (for higher θ values). This behavior was observed for w up to close to the w_{opt} and above that the M_R decreased for the whole range of θ. The missing data are due to failure of the specimen with a high w undergoing excessive PD.

Plots of the parameters k_1 and k_2 as functions of S are shown in Figure 4(b). In this case, k_1 decreased and k_2 increased when S increased. It can also be seen in Figure 4(a) that several of the M_R versus θ curves cross each other for the different ws inferring that k_2 was not constant here with respect to w. Attempts to fit the sigmoidal MEPDG M_R-moisture model, stated in Equation 2, for the entire range of stress levels (θ) of the PD tests following the procedure suggested by Andrei (2003) was not successful. The reason is that this model assumes decrease in M_R with increased w (as a sigmoidal function) for all values of θ regardless of any possible increase in M_R resulting from PC. On the other hand, it was possible to model the moisture dependency of the M_R in the PD tests as shown in Figure 5, by applying Equation 4 and expressing k_2 as a linear function of S (Figure 4(b)). However, in general, this expression of k_2 is dependent on the amount of PC which should also be included in the model.

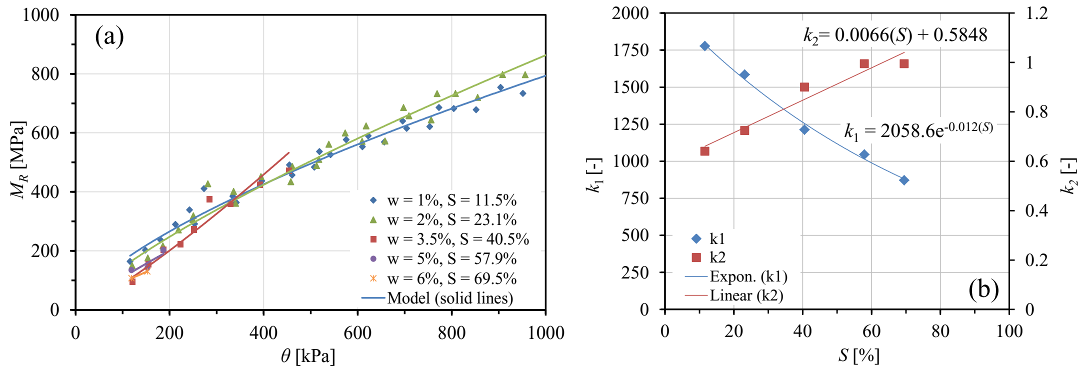

Figure 4: PD tests: (a) M_R as a function of θ for various w and S, (b) k_1 and k_2 as a function of S

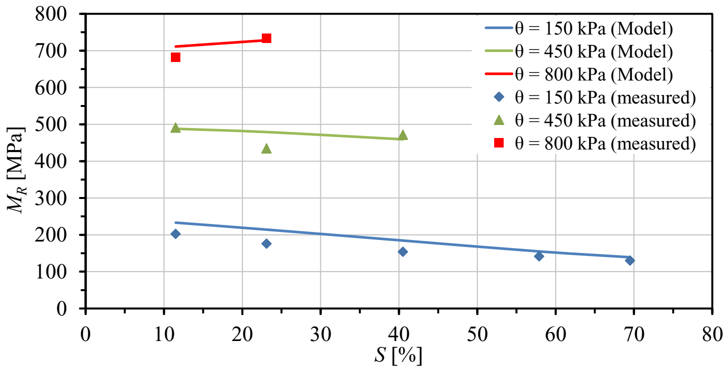

Figure 5: M_R as a function of S for various θ (PD tests): measured vs. modelled (proposed model)

4.3 Analysis of the Results

The results were further investigated by plotting the M_R values for a few stress paths against N for the PD tests. Figure 6(a) illustrates the accumulated permanent strain ($\hat{\varepsilon}_p$) with N for w = 2% and w = 3.5%, including the shakedown ranges occurring for the different stress paths, calculated according to Equation 3 (Rahman and Erlingsson 2015). Figure 6(b) illustrates the change in the M_R with N for a few selected stress paths covering the three shakedown ranges. For shakedown ranges A and B, it was found that the M_R was fairly constant with respect to N (stress path 7 and 9 in Figure 6(b) when w = 2%). But in the case of shakedown range C, it increased with N (stress path 12 when w = 2% and stress path 4 and 6 when w = 3.5% in Figure 6(b)). For example, for stress path no. 12 in Figure 6, with w = 2%, the increase in the M_R was about 11% from the 2,000th to the 10,000th load cycle. A similar trend was observed by Werkmeister et al. (2001). For the test with w = 3.5%, almost all of the stress paths were in shakedown range C where the M_R increased with N for most of them. This resulted in a more rapid increase of the M_R with N for the test with w = 3.5% compared to the test with w = 2%. Comparing the two PD plots, the test with w = 3.5% showed a much higher PD, which was probably due to the PC. Thus the possible explanation is that in the MS RLT tests, moisture aided the PC, reorientation and change in packing arrangement of the particles which in turn increased the M_R of the material (Yideti et al. 2013, Liu et al. 2014). Thus when the w was increasing up to close to the optimum, the material experienced a faster PC aided by moisture that resulted in increased M_R. This led to the steeper M_R versus θ curves for the specimens with a higher w. For some instances this resulted in an even higher M_R for a specimen containing higher w during the later stages of the tests.

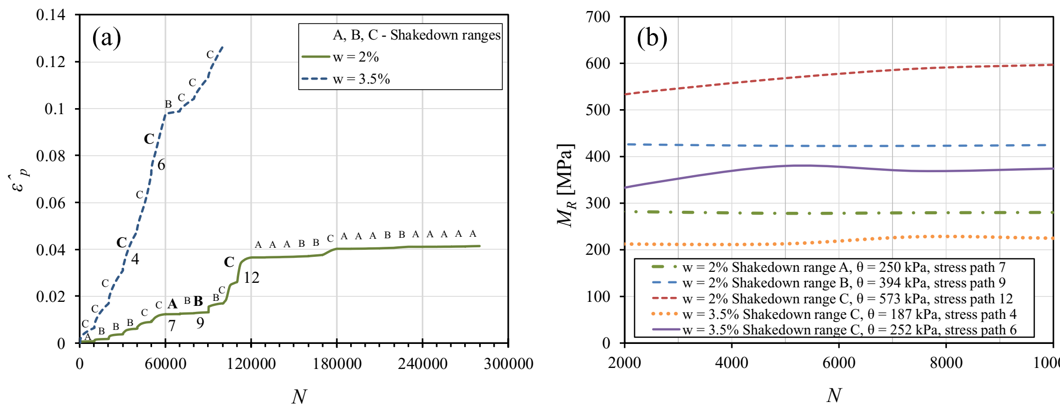

Figure 6: Evolution of M_R with N and PD for different shakedown ranges (w = 2% and 3.5%, PD test)

5 Conclusions

This study showed some difference in the impact of moisture on M_R depending on the associated PC in the RLT test environment. It was observed that with increased moisture, M_R decreased when PC was negligible. On the other hand, large amount of PD and PC may lead to stiffening of the specimen aided by moisture that may result in some apparent increase in the M_R with increased moisture. However, this increase in the M_R may not be of practical benefit since the pavement then experiences a large amount of PD. Nonetheless the models should be able to predict the behavior of the material in all practical scenarios as accurately and as reliably as possible. Because of the impact of PC on the moisture sensitivity of M_R, while the MEPDG M_R-moisture model worked well in the former case, it failed in the latter case. This implies the necessity of an improved model that may handle both situations with better reliability. Even though the modelling approach presented here worked well for both situations for the specific case presented here, the amount of PD or PC should be included in it and it needs further verification with more tests on more materials. It is also necessary to develop an alternative model to predict the moisture dependency of M_R of UGMs based on other material properties, similar to that proposed for subgrade materials (Rahim and George 2005). Thus the material specific parameters a_1 and a_2 in Equation 4 needs further exploration with a variety of materials.

This was a limited study based on laboratory RLT tests where the variables were better controlled compared to field conditions. In reality there are many factors that may influence the results and the effect of PC may not be readily observable in all cases. Hence the findings of this study should be further validated more RLT tests on more materials as well as with field observations.

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