Moisture Sensitivity of the Deformation Properties of Unbound Granular Materials

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ABSTRACT: A series of Repeated Load Triaxial (RLT) tests was carried out on a typical Unbound Granular Material (UGM), used as base layers in thin flexible pavements. The tests were performed with different moisture contents to enhance the understanding of the effect of moisture on the deformation properties that may be used for future modeling and design. The grain size distributions of the materials were altered to study the effect on the moisture sensitivity. The influence of moisture on the resilient deformation properties was investigated using the resilient test protocol from the European standard. An existing stress dependent resilient modulus (M_R) model was calibrated using the test data and the variation of the model parameters with moisture was investigated. The parameters of a moisture-dependent M_R model were also studied for their dependency on the grain size distribution. The multi-stage (MS) loading approach according to the European standard was used to obtain information about the influence of moisture on the permanent deformation characteristics. Results indicate that both the resilient and permanent deformations increase with increasing moisture content. These effects are more pronounced for materials with finer grading.

KEY WORDS: Unbound Granular Materials, Resilient modulus, Permanent deformation, Repeated Load Triaxial Test, Moisture.

1 INTRODUCTION

In thin flexible pavements, the base and sub-base layers, comprised of Unbound Granular Materials (UGMs), play a vital role in maintaining the structural integrity. The deformation behavior of UGMs under external loading can be characterized as complex elasto-plastic with a recoverable or resilient deformation part and a plastic or permanent deformation part (Erlingsson and Magnusdottir, 2002). Resilient deformation of the base layer is associated with fatigue cracking of the asphalt layer while plastic deformation is responsible for the development of rutting. Analytical design of flexible pavement structures requires proper understanding and modeling of these deformation properties. Besides stress levels, moisture is considered to be one of the factors that have a substantial impact on the deformation behavior of UGMs (Cary and Zapata, 2011, Erlingsson, 2010, Rahman and Erlingsson, 2012, Lekarp, 1999, Ekblad, 2007). Predictions of variations of these properties with seasonal variation of moisture are therefore essential for a sustainable design approach.

The aim of this work is towards a better understanding of the influence of moisture on the mechanical performance of UGMs with an ambition to take them into account in future pavement modeling and design. This study involves analysis of resilient and permanent deformation properties of UGMs under variation in moisture content using Repeated Load Triaxial (RLT) tests. The RLT test is a standard way of simulating the in-pavement stress conditions in the laboratory where cyclic stresses are applied on a prepared cylindrical specimen and the corresponding deformations are measured. From the generated data, the resilient and permanent deformation properties are evaluated.

2 DEFORMATION BEHAVIOR OF UGM

In a UGM the total induced strain due to single load pulse consists of elastic and plastic strains which can be expressed as:

$$\varepsilon_{tot} = \varepsilon_r + \varepsilon_p \tag{1}$$

where ε_{tot} is the total axial strain, ε_r is the axial elastic strain and ε_p is the axial plastic strain. Usually, the elastic strain consists of the largest part of the total strain with only a small part due to the plastic strain (Erlingsson and Magnusdottir, 2002). In RLT test, the cylindrical specimen is subject to a constant confining pressure, σ_c (constant confining pressure method) and a cyclic deviator stress, $\sigma_{d.}$ Thus, the principal stresses acting on the specimen are: $\sigma_1 = \sigma_3 + \sigma_d$, and $\sigma_2 = \sigma_3 = \sigma_c$.

2.1 Resilient deformation characteristics

The resilient deformation characteristics are quantified using the resilient modulus, M_R which is an estimate of the stiffness modulus of the specimen for rapidly applied loads, calculated as (Huang, 2004):

$$M_R = \frac{\sigma_d}{\varepsilon_r} \tag{2}$$

where ε_r is the resilient (recoverable) axial strain, taken after several load repetitions when the deformations are stabilized.

M_R is dependent on the state of stress, measured as the sum of the principal stresses, called the bulk stress, $\theta = \sigma_1 + \sigma_2 + \sigma_3 = \sigma_1 + 2\sigma_3$. The variation of 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:

$$M_R = k_1 p_a \left(\frac{\theta}{p_a} \right)^{k_2} \tag{3}$$

where, k_1 and k_2 are regression parameters and p_a is a reference pressure or atmospheric pressure taken as 100 kPa. For this study, the regression parameters of this model were determined using the RLT test data and the influence of moisture on these parameters were analyzed.

The effect of moisture on M_R can be expressed using the M_R-Moisture model proposed by Andrei (2003) which is a slight modification to the current Mechanistic Empirical Pavement Design Guide (MEPDG) model by AASHTO (The American Association of State Highway and Transportation Officials) (ARA, 2004). This model simplifies the MEPDG model by eliminating density as a variable and using gravimetric moisture content as predictor variable instead of degree of saturation:

$$\log_{10}\frac{M_R}{M_{Ropt}} = \log_{10} a + \frac{\log_{10} b - \log_{10} a}{1 + EXP(\beta + k_w(w - w_{opt}))} \tag{4}$$

where,
w = gravimetric moisture content expressed as decimal
w_{opt} = gravimetric optimum moisture content expressed as decimal
M_{Ropt} = resilient modulus at optimum moisture content
a = the minimum value of the ratio M_R/M_{Ropt}
b = the maximum value of the ratio M_R/M_{Ropt}
k_w = regression parameter dependent on material properties
and β is expressed as,

$$\beta = \ln_e\left(\frac{-\log_{10}(b)}{\log_{10}(a)}\right) \tag{5}$$

2.2 Permanent deformation characteristics

Compared to resilient properties, permanent deformation behavior of UGM is less studied and less understood (Gidel et al. 2001, Uzan, 2004, Hornych et al. 2004). Permanent deformation accumulates with the number of load applications and its development is very much dependent on stress levels. Werkmeister et al. (2001) investigated the development of permanent deformation in UGM using the shakedown concept. They identified three shakedown ranges for UGM, shown in Figure 1, depending on stress levels. In shakedown range A (Plastic shakedown), after a post-compaction period, the material stabilizes and the deformation becomes entirely resilient with no further permanent strain. Range B (Plastic creep) represents an intermediate response where the permanent strain per cycle continuously decreases or becomes constant without complete stabilization. In range C (Incremental collapse), the permanent strain rate continues to increase leading to failure.

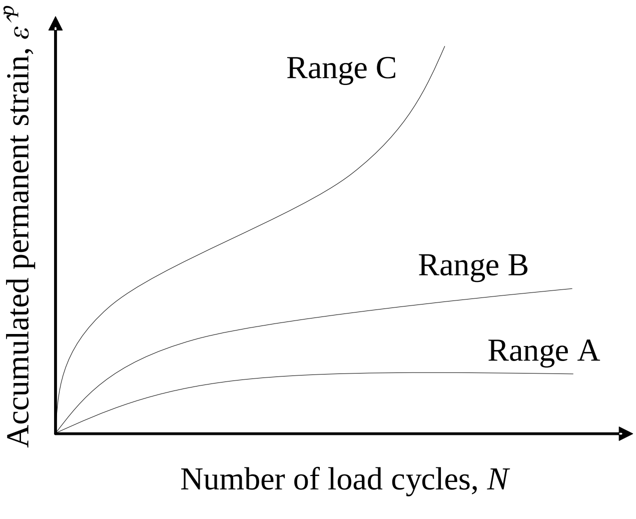

Figure 1: Different types of permanent deformation behavior, depending on stress level (Arnold et al. 2002).

Lekarp (1999) have summarized the permanent deformation models found in literature, dividing them as relationships describing the influence of the number of load applications and relationships describing the influence of applied stresses. A more recent model proposed by

Korkiala-Tanttu (2005) is presented here. This model is based on classical soil mechanics that takes into account the effect of stress levels together with the number of load repetitions:

$$\hat{\varepsilon}_p(N) = CN^b \frac{R}{A-R} \tag{6}$$

where, $\hat{\varepsilon}_p(N)$ is the accumulated permanent strain after N number of load cycles, C and b are material parameters. A is assumed to be independent of the material (A = 1.05). R is the shear stress ratio which is the ratio of the applied deviator stress to the deviator stress at failure, determined using static triaxial test.

Although moisture is found to have significant impact on the permanent deformation behavior of UGMs, a fully-developed moisture-dependent permanent deformation model has been lacking. The current study is an attempt by the authors to obtain a better insight about the permanent deformation characteristics with an aim to develop a moisture-dependent permanent deformation model in the future.

3 LABORATORY TESTING

To study the effect of moisture on the deformation behavior of UGMs, a series of RLT tests was carried on a crushed rock aggregate with different moisture contents and grain size distributions. To evaluate the resilient properties, the test for resilient modulus at constant confining pressure from the European standard EN-13286-7 (CEN, 2004b) was followed. The multi-stage (MS) loading method from the same standard was used to evaluate the permanent deformation characteristics. For the tests, the 'high stress level' from the standard was used. Cylindrical specimens of 150 mm in diameter and 300 mm in height were prepared with target moisture contents and densities using a vibrocompactor. The axial deformations were measured using three linear variable displacement transducers (LVDTs), 120° apart, anchored to the middle third of the specimen. The loadings used for the tests were haversine pulses with a frequency of 10 Hz with no rest period. The details of the RLT test setup can be found in Rahman and Erlingsson (2012).

4 MATERIALS TESTED

The material used for this study is a crushed rock aggregate, typically used as base course material, obtained from Skärlunda in Sweden. It is characterized as foliated medium-grained granite with quartz, K-feldspars and plagioclase as main constituents (Ekblad, 2007). The grain size distributions used were derived using the equation:

$$P = \left(\frac{d}{D_{\max}} \right)^n \tag{7}$$

where, P is the percentage smaller than sieve size d, D_{max} is the maximum particle size and n is the grading coefficient describing the shape of the curve (Fuller, 1905). For this study, the grain size distributions were altered by varying n, shown in Figure 2. The maximum particle

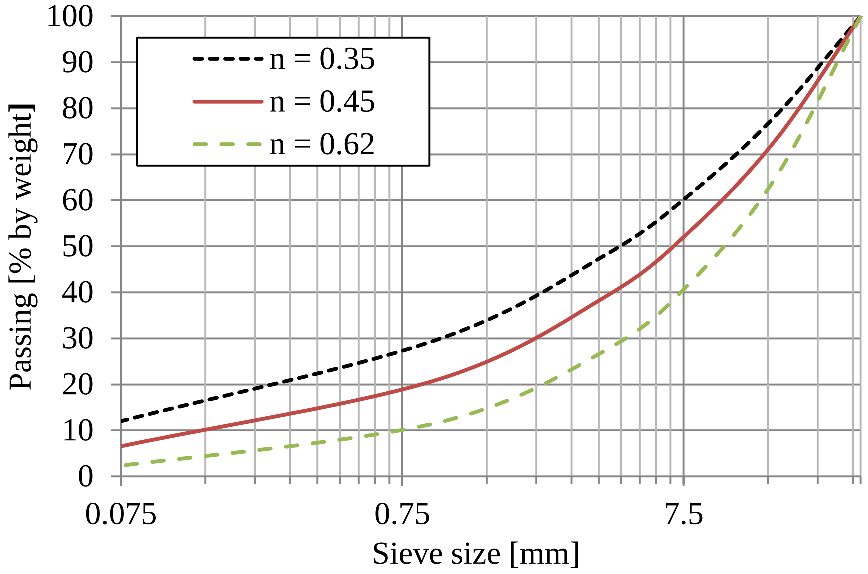

Figure 2: Particle size distributions.

size used was 31.5 mm. The modified Proctor method according to the European Standard EN 13286-2 (CEN, 2004a) was used to determine the optimum moisture contents and the maximum dry densities. The specimens were compacted to 97% of the maximum dry density. Properties of the specimens have been summarized in Table 1.

Table 1: Material properties.

Grading coefficient, *n*	Optimum moisture content (% by weight)	Maximum dry density (g/cm^3)	Fine content (%) (< 0.075mm)	Specific gravity [-]
0.35	6.5	2.22	12	2.64
0.45	6.0	2.26	6.5	2.64
0.62	5.5	2.11	2	2.64

5 RESULTS AND DISCUSSION

5.1 Resilient tests

The resilient tests were performed with gravimetric moisture contents (w) starting at 1% with an increment of 1% each time up to close to saturation, where it was possible to carry on the tests with sufficient accuracy. For clarity, only a few of the results for n = 0.35 are plotted in Figure 3. Results showed that M_R was affected by moisture - it decreased as moisture content increased. The parameters of the k-θ model were optimized using the least square curve fitting method, employing the Solver add-in in Microsoft Excel. Plots of these parameters as a function of moisture content are shown in Figure 4. It is observed that, the parameter k_1 decreased with increasing moisture content. This decrease was more pronounced for the finer grading indicating greater sensitivity to moisture. On the other hand, the parameter k_2 was less affected by moisture. The values of both the parameters k_1 and k_2 were also influenced by the grading coefficient.

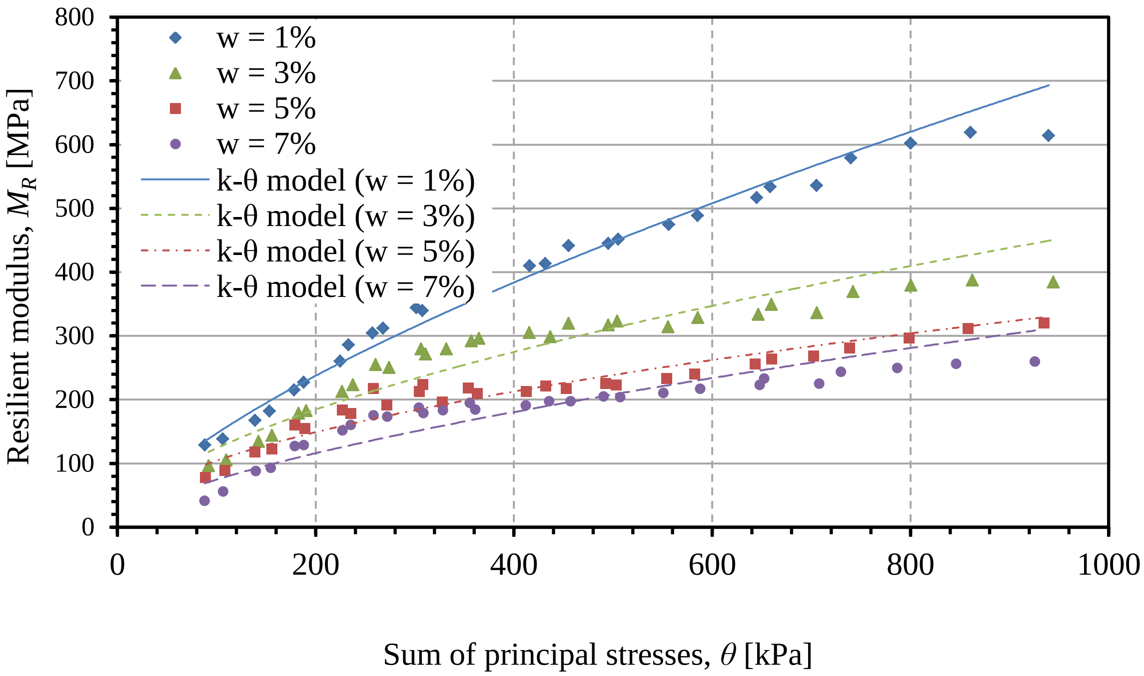

Figure 3: M_R as a function of θ at various moisture contents (n = 0.35).

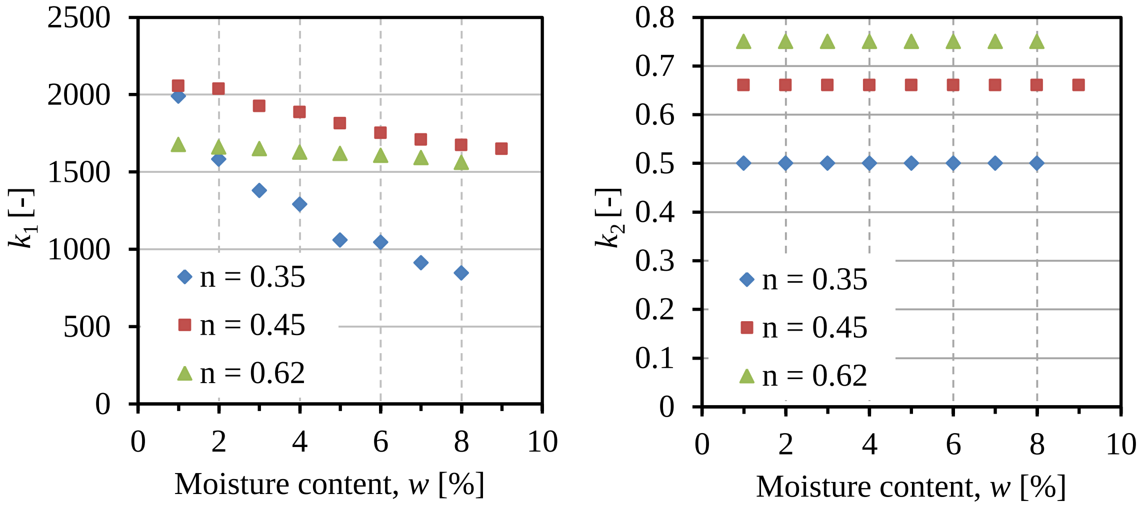

Figure 4: The parameters k_1 *and* k_2 as a function of moisture content.

A plot of the resilient moduli (normalized as M_R/M_{Ropt}) as a function of change in moisture content with reference to the optimum is shown in Figure 5. The M_R-moisture model, stated in Equation (4), was calibrated using these data by optimizing the parameters with Solver. For the M_R-Moisture model, the values of M_R at a typical state of stress θ =550 kPa were used. These fitted models are also shown in Figure 5. The parameters of the model are presented in Table 2. Visual observation and the coefficient of determination (R^2) values in Table 2 suggest that very good quality of fits were obtained with the M_R-moisture model. It is also reflected that the finer grading was more sensitive to moisture variation. From Table 2, it is observed that the values of the parameters a and k_w decreased while b and β increased as the grading got finer (decreasing n).

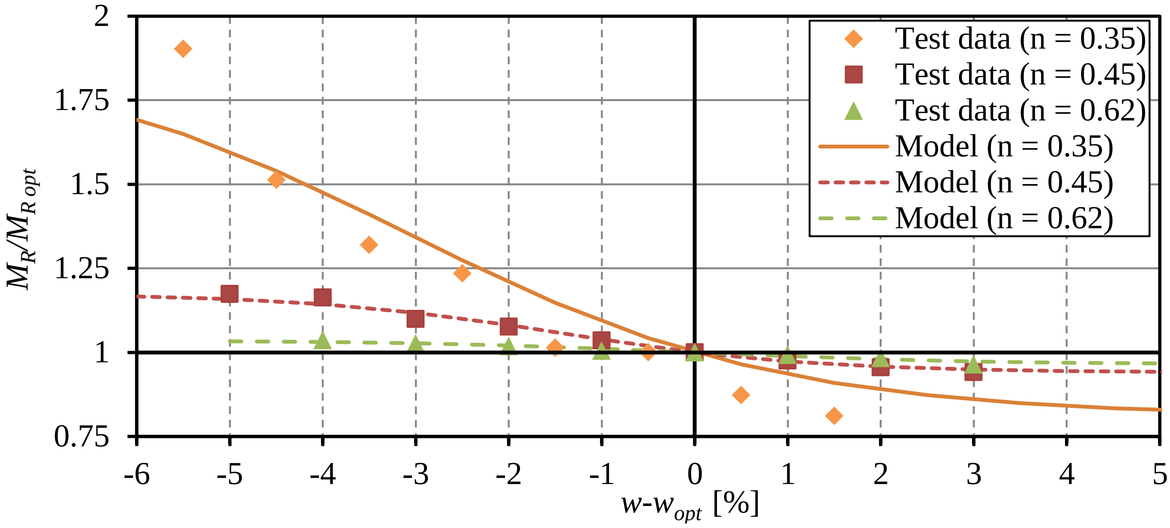

Figure 5: Resilient modulus ratio as a function of moisture content variation (for θ = 550 kPa).

Table 2: Parameters of the M_R-moisture model.

Grading coefficient, *n*	Parameters				R^2
	a	*b*	β	k_w	
0.35	0.810	1.902	1.118	49.545	0.887
0.45	0.941	1.174	0.961	74.473	0.984
0.62	0.964	1.036	-0.036	84.842	0.955

5.2 Permanent deformation tests

The effect of moisture on permanent deformation behavior was studied using MS RLT tests on specimens having different moisture contents. The accumulation of permanent deformation with the number of load cycles at different moisture contents are shown in Figure 6. Results indicate that the permanent deformation increased as moisture increased and it increased dramatically when moisture content reached a certain level. This was especially true for material with higher fine content. Comparing the three plots, it is noted that at drier state (1% moisture content) all the three grain size distributions showed similar permanent deformation behavior. However, when moisture increased, the finer grading was more affected, showing higher permanent deformations.

Visual observation of the curves reveals that at low moisture contents, permanent deformations stabilized for most of the stress paths in the MS RLT test, showing behavior similar to shakedown range A. With the increase in moisture content, the behavior for the same stress paths became increasingly unstable shifting from shakedown range A to range B or to range C which implies that the material was getting prone to collapse. For the material with higher fine content, only a small increase in moisture significantly changed its behavior. For modeling, the moisture content that changes the permanent deformation behavior from shakedown range A to B or C needs to be identified. This may be taken into consideration in pavement design and management systems where the moisture content will be maintained below this level and a proper selection of grain size distribution will be used. If the moisture content crosses this limit, load restrictions should be applied to prevent excessive rutting or failure. However, further work is necessary to establish this.

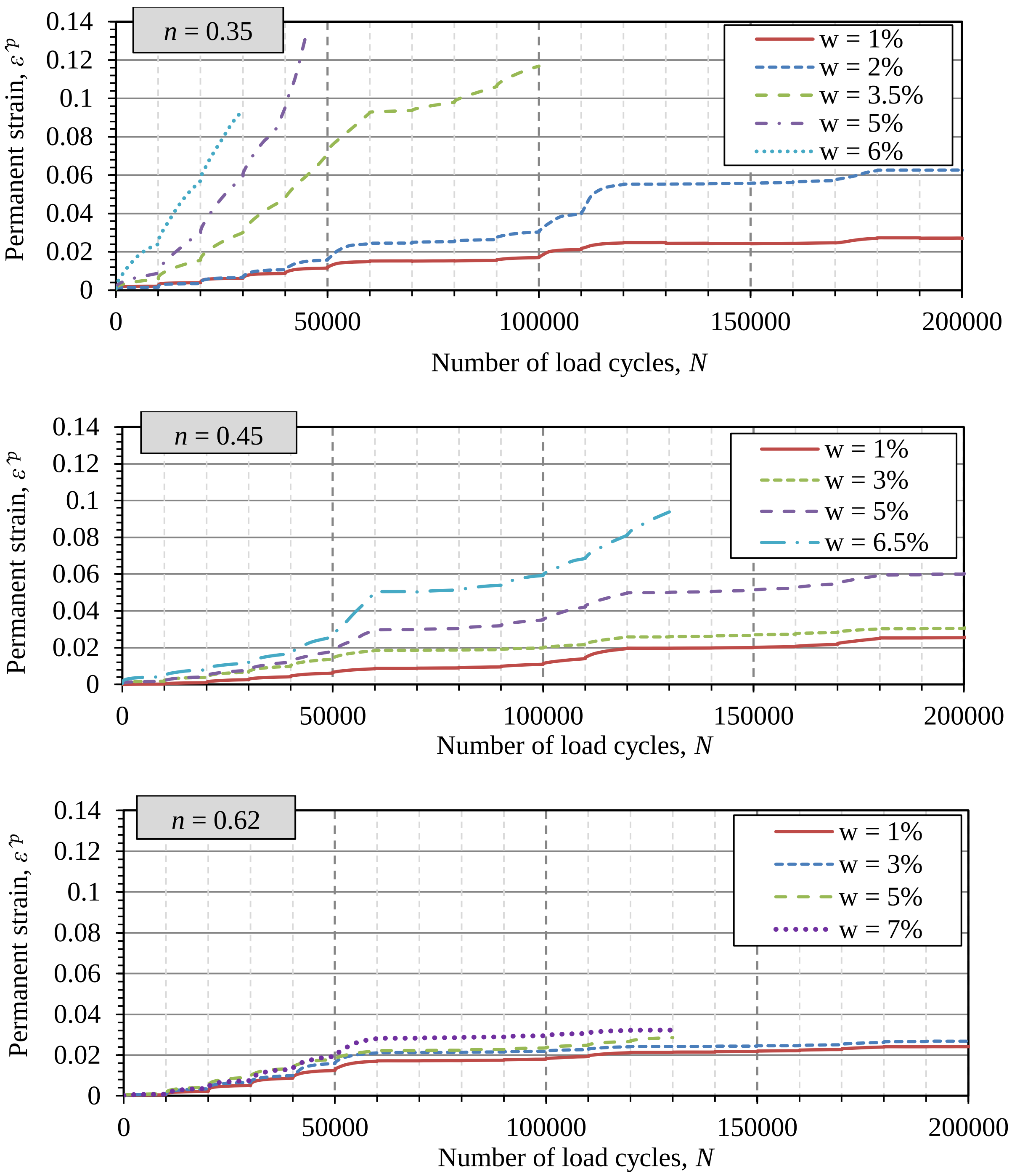

Figure 6: Accumulation of permanent strain with load repetitions for different moisture contents.

6 CONCLUSIONS

This study was carried out to investigate the influence of moisture on the deformation behavior of UGM and the effect of grain size distribution on the moisture sensitivity. It was based on RLT tests in the laboratory on a typical Swedish UGM. The k-θ model and the M_R – moisture model were calibrated using the test data and the effects of moisture and grain size distribution on the parameters of these models were analyzed. Based on this study, the following conclusions can be drawn:

- Moisture significantly affects both the resilient and permanent deformation properties of UGM.
- Resilient stiffness, M_R decreases with increasing moisture content.
- The range of variation of M_R is dependent on the grain size distribution. Finer grading shows larger variation.
- The parameter k_1 of the k-θ model decreases with increasing moisture. This is more pronounced for finer grading. The parameter k_2, on the other hand, is relatively insensitive to moisture. Both these parameters are affected by the grain size distribution.
- Satisfactory quality of fit to the RLT test data may be obtained with the M_R-Moisture model. The parameters of the model are influenced by the grain size distribution.
- Accumulation of permanent deformation in the MS RLT test increases significantly with increased moisture.
- Accumulation of permanent deformation starts to increase dramatically after a certain moisture content and the material starts to collapse for further increase in moisture.
- Permanent deformation behavior can change from shakedown range A to shakedown range B or C for the same stress levels with increase in moisture.

Since for thin flexible pavements, resilient deformation of UGM is related to fatigue cracking and permanent deformation of UGM is related to rutting, the results from this study may imply that increase in moisture in the pavement structure imposes greater risk of developing both fatigue cracking and rutting. Providing effective drainage and proper selection of material gradation could minimize the risks. There is a possibility to identify a critical moisture content for a UGM with a specific grading, after which the material becomes unstable. This could be used for pavement modeling and designing and also to maintain the drainage system to keep the pavement moisture level below this critical limit and to impose load restrictions, if necessary.

However, this study was carried out only on one crushed rock aggregate. The conclusions drawn here should be verified with more tests with different materials. Replicate tests should be performed as well, to account for the experimental dispersions in the RLT tests. The models used here should be calibrated and validated for various other materials and may need to be improved accordingly. Since moisture is found to have a great impact on the permanent deformation behavior, development of a moisture-dependent permanent deformation model is essential for a successful analytical design approach.

7 ACKNOWLEDGEMENTS

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