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Influence of the water permeability on the performance of basecourse aggregates

Influence de la perméabilité à l'eau sur les performances de l'agrégat de base

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ABSTRACT: Aggregates are a necessary and important resource for the construction and maintenance of pavements worldwide. In order to reduce the risk of early pavement failure, it is crucial to use basecourse aggregates which show high resistance against plastic deformation in both- wet and dry conditions, especially for very highly trafficked pavements.
The use of high quality and water permeable UGMs significantly improve the rutting performance of the basecourse and hence, that of the whole pavement structure. However, current procedures do not give detailed information as to which UGMs should be selected in order to provide sufficient rutting resistance/performance along with water permeability.
This paper reports on one aspect of an investigation conducted by TU Dresden, which is aimed at determining the influence of the water permeability on the performance of basecourse aggregates using the results of RLT and water permeability tests. The testing regimes used and test results are discussed in this paper.

RÉSUMÉ: Les granulats sont une ressource nécessaire et importante pour la construction et l'entretien des chaussées dans le monde entier. Afin de réduire le risque de défaillance prématurée des chaussées, il est essentiel d'utiliser des agrégats de base offrant une grande résistance à la déformation plastique par temps sec et humide, en particulier pour les chaussées à trafic élevé. L'utilisation d'UGM de haute qualité et perméables à l'eau améliore de manière significative les performances en ornières du parcours de base et donc de l'ensemble de la structure de la chaussée. Cependant, les procédures actuelles ne fournissent pas d'informations détaillées sur les UGM qui devraient être sélectionnés afin de fournir une résistance / performance en ornière suffisante, ainsi qu'une perméabilité à l'eau. Ce document présente un aspect d'une enquête menée par TU Dresden, qui visait à déterminer l'influence de la perméabilité de l'eau sur les performances des agrégats du cours de base à l'aide des résultats des tests de RLT et de perméabilité à l'eau. Les régimes de test utilisés et les résultats de test sont discutés dans cet article.

Keywords: Unbound granular materials, water permeability, Repeated load triaxial tests, deformation performance, large scale laboratory tests

1 INTRODUCTION

Unbound Granular Layers (UGL) commonly used in pavements in Germany consist of gravel or crushed aggregates. These UGL play an important role in the structural performance especially for thin-surfaced asphalt pavement structures. According to the German guidelines (e.g. ZTV SoB-StB), a sufficient water permeability and bearing capacity is required for the UGL. They also show a stress dependent elasto-plastic behaviour under cyclic loading. Thus, an understanding on the shear strength, elastict and plastic deformation behavior along with the permeability of the Unbound Granular Materials (UGM) and the subgrade are essential in order to have effective usage on the materials in pavements.

The bearing capacity in-situ is described in Germany by a specific E_{v2}-value determinded by the results of the plate bearing tests which depends on the traffic volume, pavement structure and layer thickness, while as of now, there is no clear defined value or range available for sufficient water permeability. Owing to the lack of clarity as to which value represents sufficient water permeability for a defined pavement structure, Germany has no official testing procedure designated for the water permeability estimations at the moment.

Minor attention is paid to sufficient water permeability presently. It is assumed that a grading within the grading limits required leads to a sufficient water permeability of the UGL. Although it has been seen in Germany that despite the UGM grading being within the limits especially for block pavements, a sufficient water permeabilty was not achieved which therefore led to damages. Hence, the grading limits defined are not a suitable parameter to ensure an adequate water permeabilty combined with a sufficient rutting resistance.

Therefore, the deformation performance, as well as, the water permeability of the UGL are of the utmost importance. In a dry state, UGL with lower permeabilty tend to have higher deformation resistance, however, in a wet state, a higher permeabiblity is desired as the water in the layers causes the finer particles to act as a lubricant, therefore making the layers more susceptible to deformation. Due to this conflict, an optimum range for water permeabiblity needs to be determined were the materials have a sufficent stiffness and rutting resistance.

Hence, it is often discussed in Germany whether the high stiffness and rutting resistance is compatible with a sufficient water permeability of the UGL.

2 AIM OF THE RESEARCH

Aim of the research presented in this paper was to investigate the interrelationship between the bearing capacity/rutting resistance and the water permeability of UGL. In particular, this research was conducted to gain an understanding regarding to achieve a high bearing capacity also at high moisture contents on one side and a sufficient water permeability on the other side. Therefore, water permeability tests and Repeated Load Triaxial (RLT) tests were undertaken in the laboratory to determine water permeability and the performance of UGM under cyclic loading.

In addition, large scale laboratory tests were conducted to investigate the performance of these materials in-situ and to confirm the finding of the RLT tests.

2 LABORATORY TESTS

2.1 Materials tested

Laboratory tests were carried out using different UGMs. A Granodiorite (GRA) at different gradings and a crushed Sandy Gravel (SG) at one grading were tested (Figure 1). The grading for the Granodiorite materials were choosen with relatively high fine contens, to investigate the performance of these materials with slighly higher fine contents as defined in the German guidelines for UGM (grading limits for UGM).

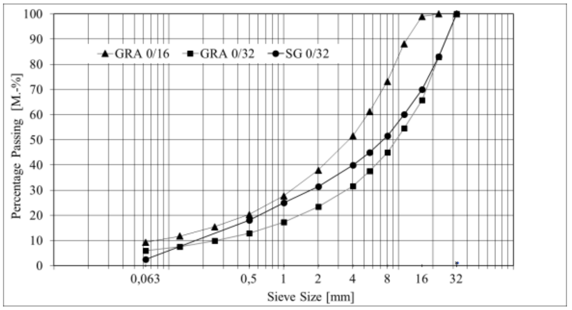

Figure 1. Grading of the GRA 0/16, GRA 0/32 and SG 0/32.

Table 1 presents the results of the Proctor tests in terms of the optimum moisture content (OMC) and the maximum dry density (MDD) for all materials.

Table 1: Results of the Proctor Tests and fine content.

	OMC (%)	MDD (g/cm^3)	Fine Content < 0.063 mm (%)
GRA 0/16	6,6	2,288	9.3
GRA 0/32	5,9	2,290	6.0
SG 0/32	6,0	2,200	3.2

In addition, frost heaving tests were undertaken on the Granodiotite materials. The results showed that the materials are not frost succeptible – even with the higher fine content.

2.2 Water Permeability Tests

Up to now, a sufficient water permeability of UGL was ensured by defining a specific grading limits in Germany. However, Wolf (WOL 2014) showed that the water permeability of UGL varies to a large extend, even if the UGL had the same grading and the same Degree of Compaction (DOC). The permeability of UGM depends on the following factors (WOL 2014):

- the grain size,
- the grain distribution,
- the grain shape and their roughness,
- the pore content,
- the hydraulic gradient and
- the viscosity of the water.

UGM are generally considered to be sufficiently permeable to water if a permeability value $k_f \geq 10^{-5}$ m/s is achieved. To measure the water permeability of UGM in the laboratory, DIN 18 130-1 (DIN 18 130-1) can be applied, using the stand pipe infiltrometer. However, this procedure is not suitable for materials with a low water permeability. Therefore, as an alternative the procedure according to DIN 18 035-5 (DIN 18 035-5) is also often used for materials were a low permeability can be expected. Hence, this testing method was used within the research project.

For the permeability tests, the samples were compacted to a target density of 103% of the MDD. Before the tests started, the samples had to remain in a water basin for 12 hours. Figure 2 shows the experimental setup used (WOL 2014).

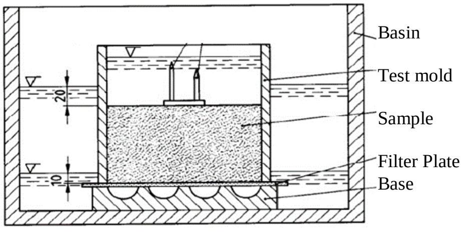

Figure 2. Water permeability testing device.

During the tests, the time Δt was measured when the water level from the first measuring tip dropped to the second measuring tip. Using the heights from the external water level and the two heights defined by the measuring tips, the two pressure height differences could be calculated. Thus, the determination of the coefficient of water permeability k_f was possible (Equation 1).

$$k_f = \frac{H_1 - H_2}{\Delta t} / \frac{\Delta h}{l} * \alpha \qquad (1)$$

Where k_f (-) coefficient of water permeability, α (-) correction factor, l (cm) sample height, Δh (cm) average pressure height difference, Δt (s) time interval, H_1 (cm) pressure height at test start, and H_2 (cm) pressure height at test end. The results of the tests are presented in Section 3.1.

2.3 *RLT Tests*

The RLT testing machine at the Laboratory of Pavement Engineering at TU Dresden was used to determine the deformation behavior of the UGM (Figure 3). The samples were tested at 70% and 85% of the OMC and 97% of the MDD (Table 1).

The test specimens were produced using a special compaction mold. The UGM was then placed in 5 to 6 layers and compacted layer by layer with a vibratory hammer. The sample size was 300 mm x 150 mm (height x diameter).

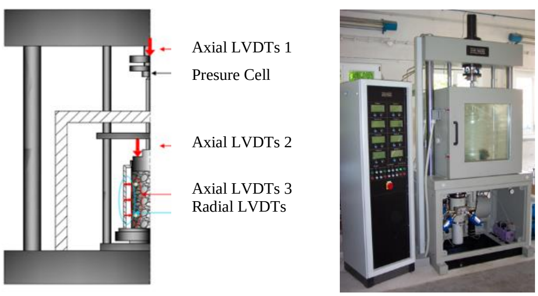

Figure 3: RLT testing device.

The deviatoric, sinusoidal vertical load was applied in all experiments with a frequency of 5 Hz while the horizontal stress was kept constant. In the RLT tests, both strain components (deviatoric and hydrostatic strains) were recorded. Before carrying out the tests to determine the elastic deformation behavior, it was necessary to apply a preload (20.000 load cycles at 10 Hz, σ_1 = 450 kPa, σ_3 = 150 kPa) to stabilize the sample.

Figure 3 shows the stress ratios applied to investigate the elastic deformation behavior.

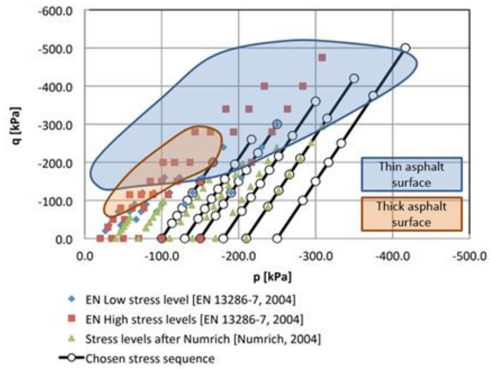

Figure 4. Stress levels for investigating the elastic deformation performance of UGMs (CAN 17)

Afterwards, a multi-stage, long-term RLT tests were undertaken in which elastic and plastic strains were recorded as a function of time. The authors propose a test protocol consisting of seven series of long sinusoidal shaped loading steps of 50,000 load cycles, each at 5Hz. The stress levels used are shown in Table 2.

Table 2. Stress levels for characterizing the plastic deformation performance of UGM during RLT tests (CAN 2017).

Test	**Cell pressure (kPa)**	**Vertical stress (kPa)**	**Number of LC (-)**
1	100	200	50,000
2	100	250	50,000
3	100	300	50,000
4	130	430	50,000
5	150	530	50,000
6	150	650	50,000
7	150	750	50,000

3 TEST RESULTS

3.1 *Water Permeability Tests*

During the experiments on the GRA it was difficult to determine the time taken for the water level to reduce from the first to the second measuring tip as the water level dropped very slowly. As a result, a weak water permeability for GRA 0/16 and 0/32 was found. However, the SG 0/ 32 showed higher values for the water permeability. Table 3 presents the results of the measurements.

Table 3: Water permeability values.

	k_f (m/s)
GRA 0/16	9,71E-08
GRA 0/32	1,28E-07
SG 0/32	1,15E-05

3.2 RLT Tests

3.2.1 Elastic Deformation Performance

The evaluation of the tests for determining the elastic deformation behavior was based on the deviatoric elastic strains. The last 10 load cycles of each load level were analysed to determine the elastic strain values. Equation 2 was used to calculate the resilient modulus M_r (Figure 5).

$$Mr = \frac{\sigma_1 - \sigma_3}{\varepsilon_{v1}} \tag{2}$$

Where ε_{1v} (10^{-3}) is the deviatoric elastic vertical strain, M_r (MPa) resilient modulus, σ_1 (kPa) vertical stress and σ_3 (kPa) horizontal stress.

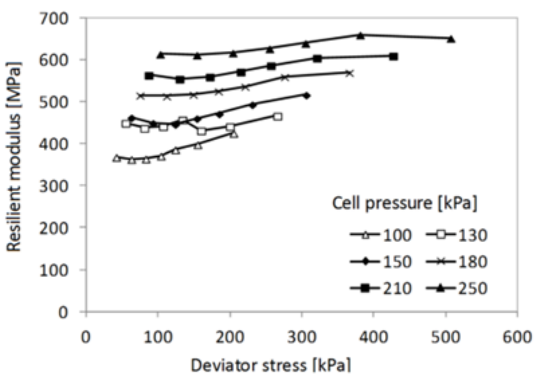

Figure 5: M_r depending on the deviatoric stress and for different horizontal stresses - GRA 0/16.

It was found that the GRA 0/16 especially at 70% of the OMC has no pronounced deviatoric stress-susceptible stiffness behavior (Figure 5). Furthermore, it can be seen from Figure 6 that the GRA 0/16 exhibits higher stiffness compared to the GRA 0/32 at low stress ratios and at 70% of OMC. This ratio is reversed at high stress conditions (Figure 7). At high water contents (here 85% of OMC) the GRA 0/32 generally shows a higher rigidity followed by the SG 0/32 compared to the GRA 0/16. This means that the GRA 0/32 is probably less sensitive to the drop in stiffness at high water contents compared to the other materials tested.

Based on the results of the RLT tests, the parameters for the Modified Universal Model (UZA 85) (Equation 3) were determined (Table 4):

$$M_r = k_1 \left(\frac{\theta}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3} \tag{3}$$

Where θ (kPa) bulk stress, τ_{oct} (kPa) octaeder stress, p_a = 100 (kPa), k_1 (MPa) material parameter, k_2, k_3 (-) material parameter (Table 4).

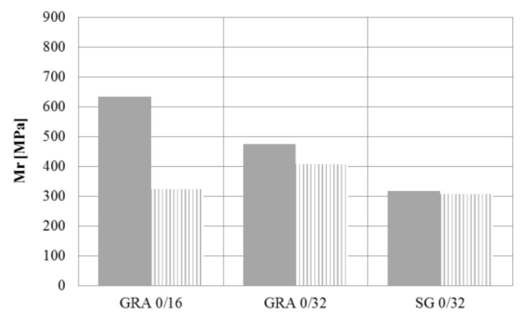

Figure 6: M_r of the materials tested, σ_1= 200 kPa; σ_3= 100 kPa (representative to low stress levels on a UGL)

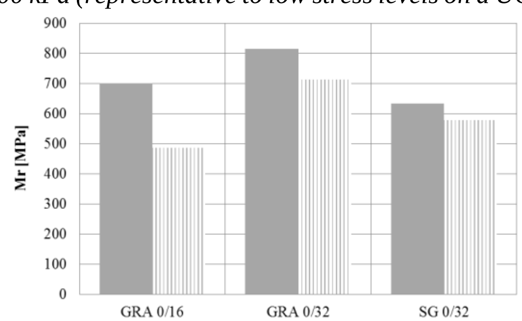

Figure 7: M_r of the materials tested, σ_1= 750 kPa; σ_3= 250 kPa (representative to high stress levels on a UGL)

Table 4: Parameter of the Modified Universal Model.

	k_1 (MPa)	**k_2** (-)	**k_3** (-)
GRA 0/16 70% OMC	646	0	0
GRA 0/16 85% OMC	172	0,42	-0,04
GRA 0/32 70% OMC	256	0,47	-0,02
GRA 0/32 85% OMC	191	0,57	-0,1
SG 0/32 70% OMC	133	0,64	-0,03
SG 0/32 85% OMC	132	0,67	-0,12

3.2.2 Plastic Deformation Performance

Furthermore, the evaluation of the RLT tests regarding the plastic deformation behavior was carried out. Figures 7 shows the deformation curves for each load level for the GRA material. It is evident that an increase in the stress state of the specimen also causes an increase of the plastic strains. Furthermore, it shows that the GRA 0/16 at the same stress level in comparison to the mixture GRA 0/32 shows significantly higher plastic deformations. This situation can be observed in both examined water contents. On the basis of these results, it can be concluded that even in the pavement, when using a GRA 0/16 in the UGL, significantly higher plastic deformations will occur compared to when GRA 0/32 is used. (Figure 8).

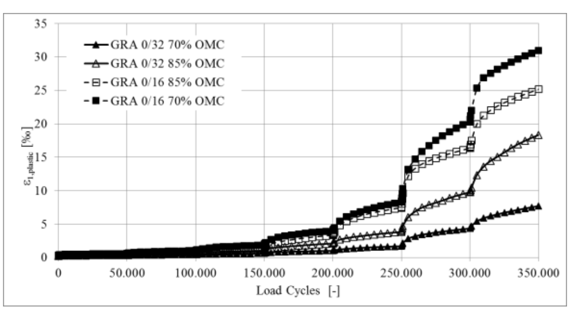

Figure 8: Vertical deformation versus number of load cycles for the 7 stress levels – GRA 0/16 and GRA 0/32

Evaluation of the RLT tests revealed a relationship between the vertical plastic strain rate and stresses (Equation 4).

$$\frac{\varepsilon_{1,p,rate}}{(L/p_a)} = c \cdot \left(e^{d \cdot \frac{q}{p}} - 1 \right) \tag{4}$$

Where p (kPa) hydrostatic stress, q (kPa) deviatoric stress, L (kPa) is given by [L= (p_2+q_2) 0.5]; and a, b, c, d (-) material parameter. The plastic strain rate was determined by the increase of the function between load cycles of 50,000 and 25,000 (Figure 8).

From Figure 9, the relative differences in the behavior of the UGM can be seen very well. At a moisture content of 70% of OMC it can be observed that the GRA 0/32 has the lowest strain rates at comparable stress states from all materials tested, followed by the SG 0/32 and the GRA 0/16. As a result, the GRA 0/32 aggregate mixture is most suitable for high stress levels when the moisture content is relatively low.

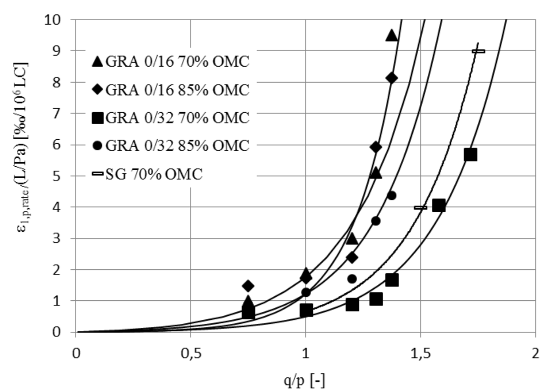

Figure 9: Plastic strain rate versus stresses

Table 5 shows the model parameter for Equation 4 of the materials tested.

Table 5: Parameter for Eq. 4 for the materials tested

	c (-)	**d** (-)
GRA 0/16 70% OMC	0,0680	3,28
GRA 0/16 85% OMC	0,0081	5,02
GRA 0/16 70% OMC	0,0169	3,41
GRA 0/16 85% OMC	0,0373	3,51
SG 0/32 70% OMC	0,0170	3,64

4 LARGE SCALE LABORATORY TESTS

Large-scale laboratory tests were carried out with the aim of investigating the deformation behavior of UGM on a scale of 1:1 under cyclic loading. To limit the effort for the large scale tests, the SG 0/32 and the GRA 0/32 which performed better than the GRA 0/16 were selected for the tests.

For this purpose, a box with steel profiles was built. This box had a floor plan of 2.5 m x 2.5 m and a total height of 1 m. Inside the box, the UGM was placed and compacted. The final layer height in the compacted state was 90 cm. The cyclic load was applied via a circular steel plate with a diameter of 30 cm and a thickness of 5cm. Figure 9 shows the test stand in its entirety.

Figure 9: Large-scale test stand

The cyclic loading of the UGLs was applied via a load plate with a load between 3 kN and 30 kN. This corresponds to stresses of 42.5 and 425 kPa (diameter of the plate of 30 cm). The maximum stress was chosen so that this size corresponds to the maximum stress that can occur in a flexible road pavement with a thickness of the asphalt layers of about 5 cm on top of a UGL.

The measurements of the deformations on the surface of the UGL were undertaken using LVDTs. To measure the deformations in the center, 3 transducers with a measuring range of 50 mm were placed on the loading plate. Displacement transducers were used to measure the deformation outside the loading plate. Figure 10 shows the position of the transducers placed on the load plate and on the surface of the UGL.

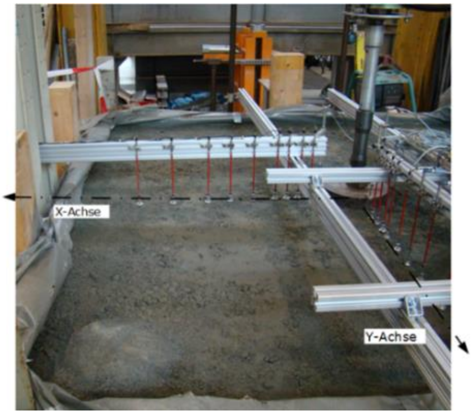

Figure 10: Location of the LVTDs to measure surface deformation

The UGMs were compacted to the same density and moisture contents as it was in the RLT tests. In total, six large-scale tests were carried out to assess the deformation behavior of UGL. The GRA 0/32 and SG 0/32 were investigated under otherwise identical conditions and repeated twice (two tests per UGM) first at 70% of OMC. This was followed by another test with an increased moisture content. In each test 1 million load cycles were applied. Figure 11 and 12 present the results of the tests.

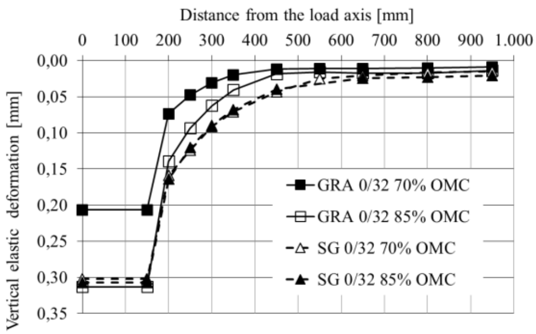

Figure 11: Vertical elastic deformation versus distance from the load axis

It was found, that with comparable moisture contents and otherwise identical conditions, the SG 0/32 showes higher elastic deformations and hence lower stiffness compared to the investigated GRA 0/32 (Figure 11). However, at higher moisture contents (85% of OMC) similar values for the elastic deformation were measured for the GRA 0/32 and the SG 0/32. At 70% of OMC both materials showed similar low plastic deformations. However, at high moisture contents the GRA 0/32 exibited higher plastic deformation, compared to the SG 0/32.

Furthermore, it was observed that for the tests at 85% of OMC, a higher water content remained in the GRA 0/32 after the tests were completed. This is presumably due to the fact that the high fine content of GRA 0/32 causes lower water permeability (see Table 3) and hence, a higher water holding capacity thus, resulting in a higher water retention percent with the addition of water. The high plastic deformation resulted at comparatively high moisture contents for the GRA 0/32 (Figure 12) compared to the SG 0/32 owing to the lubricating effect of the fine-grain-water mixture can be assumed.

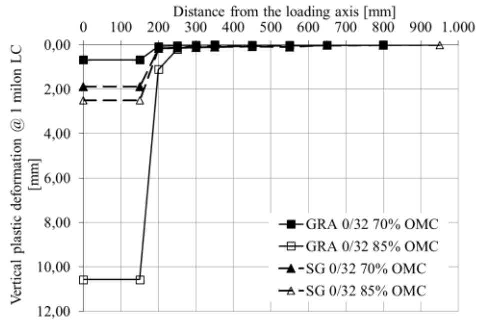

Figure 12: Vertical plastic deformation versus number of load cycles.

The results of the large-scale laboratory tests confirmed the findings from the RLT tests and showed that UGMs with a high permeability may result in a good plastic deformation performance in-situ at high moisture contents.

5 CONCLUSIONS

Basecourse aggregates are a necessary and important resource for the construction and maintenance of pavements worldwide. In order to reduce the risk of early pavement failure, it is crucial to use basecourse aggregates that show high resistance against plastic deformation in both- wet and dry conditions, especially for very highly trafficked pavements.

The use of high quality and water permeable UGMs significantly improve the rutting performance of the basecourse and hence, that of the whole pavement structure.

The paper shows the results of permeability, RLT and large scale laboratory tests using different UGM which were used to determine the influence of the water permeability on the performance of basecourse aggregates. Different materials commonly used in the basecourse of German roads were tested at different water contents. First of all, the resistance against frost heaving was proofen.

The results of the tests under cyclic loading showed a strong dependency of bearing capacity and permanent deformation on the moisture content and the stress level. It was found, that

UGMs with relatively high water permeability showed a very good plastic deformation performance in-situ at high moisture contents. It can be concluded that UGM with a high permeability should be used in pavements where high moisture contents (e.g. block pavements) may expected in the UGL. This is only referring the rutting / bearing resistance due to high trafficked loads.

Based on the RLT test results, materials (here the Granodiorite 0/32) could be identified which show high stiffness at low and high moisture contents. For high trafficked asphalt pavements these UGM with high stiffness values are recommended, because they provide a stiff base for the asphalt layers in order to have a positive effect regarding the fatigue life. This advantage regarding the high stiffness which may results in a thickness reduction of the pavements layers can be evaluated only within a analytical design procedure when the nonlinear elastic deformation performance of the UGL is considerd. These finding from the RLT tests could be confirmed by the large scale laboratory tests.

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