Adhesion Agents influencing the Fatigue Life of Stone Mastic Asphalts

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ABSTRACT: The moisture regime associated with a pavement has a major influence on the pavement performance. For this reason different test procedures on loose and compacted mixes are currently in use to investigate the impact of moisture on performance characteristics of asphalt mixtures. Presented in this paper are experimental studies on the moisture susceptibility of different asphalt mixes with respect to their fatigue characteristics. A fully coupled 3-phase hydro-mechanical model for variably saturated bound and unbound granular materials is used. The model is capable of accounting for generation and dissipation of pore and air water pressure in pavement materials subject to traffic loading. The matrix deformation, the pore water pressure and the pore air pressure are defined as five primary variables in a three-dimensional initial boundary value problem. The models are coupled using the effective stress concept for unsaturated porous media.

KEY WORDS: Adhesion agents, fatigue life, moisture.

1 INTRODUCTION

Adhesion between bitumen and aggregates needs to be strong and durable under all prevailing conditions of traffic and environment. In many countries across the world asphalt pavements are constantly exposed to water. It is well known that the material properties of asphalt mixtures are highly dependant on the moisture content. However, this problem hitherto has received little attention and is not adequately addressed in the design standards.

In order to study the influence of moisture on the fatigue life of asphalt surface mixtures research has been conducted at the Dresden University of Technology. Different test procedures are currently being used to investigate the impact of moisture on the performance characteristic of asphalt mixtures, e.g. the adhesion between bitumen and aggregates. These tests can be divided in two groups; (A), loose mix tests (DIN EN 12697-11) to determinate aggregate coating properties during water immersion, and (B), tests to be conducted on compacted mixes (DIN EN 12697-12) to evaluate the remaining strength / stiffness or other mechanical properties of asphalt mixes when exposed to water.

Using the Rolling Bottle Test (DIN EN 12697-11, Jørgensen 2002) the adhesion between aggregates and bitumen can be ranked for different bitumen/aggregate combinations. The Indirect Tensile Strength Ratio is a widely used characteristic value to evaluate the effect of moisture on the tensile strength for different asphalt mixes with and without adhesion agents. Nevertheless, it is not possible to describe the impact of moisture on the fatigue life with the tests that are currently available. However, gaining information on the fatigue life of asphalt mixes is crucial for the analytical pavement design process. Therefore, Cyclic Indirect Tensile Tests (AL Sp-Asphalt 09) are conducted to determine the fatigue life depending on the moisture impact.

The theoretical framework presented in this paper is part of an ongoing research at The University of New South Wales to move away from empirical approaches to account for moisture and moisture damage, and introduce developments based on principles of continuum mechanics. Models based on sound theoretical basis enable realistic predictions of failure pattern in pavements under the given environmental and traffic loading, and provide means to achieve performance oriented design instead of traditional design. Through such developments, it will be possible to better cope with the future challenges in pavement design and construction. This is particularly important given the current trends to deviate from the construction of conventional pavements and adopt more advanced designs such as permeable pavements.

The fact that pavements or parts of the pavements might be fully or partly saturated with water carries additional effects that differ from conventional methods of pavement design. It must be understood that in pavements a mechano-hydraulic interaction between water, air and solids takes place when vehicles traverse the pavement. This interaction has a significant impact on the load bearing behaviour of pavements, and hitherto has not received much attention.

2 LABORATORY TESTS

2.1 Materials

Several materials were chosen for the manufacturing of eight different asphalt mixtures. The different materials are denoted by [D], [G], [R], [V], [0] and [1]. In particular,

- two different aggregate types – diabase [D] and biotite-granodiorite [G]
- bitumen 50/70 from two different sources – Russia [R] and Venezuela [V]
- without [0] and with [1] 0.3% adhesion agent relating to the bitumen mass

were used to produce eight asphalt mixes of a stone mastic asphalt SMA 11 S.

2.2 Sample Preparation

For the Rolling Bottle Test the aggregates were dried and the 8/11 fraction was selected. A given amount of aggregates were mixed with the bitumen and the bitumen/adhesion agent mix mentioned above.

Additionally eight asphalt mixes were produced in the laboratory using a laboratory mixer. Asphalt slabs with a dimension of 320 by 260 by 40 mm were manufactured using a segmented roller compactor. Thereafter, the specimens were cored out of the slabs. The samples were cleaned and dehumidified. Further, the air void content and the dimensions of each specimen were determined. Since it is known that the air void content greatly affects the results of the water sensitivity tests, the air void content of the samples checked. The air void content was regulate to be between 4.5 and 6.8 Vol.-%, which is in line with the test requirements.

2.3 Bitumen Properties

The properties of the bitumen [R] and [V] were determined for delivery conditions and after thermal exposure (RTFOT - rolling thin film oven test) according DIN EN 12607-1. The following characteristic values were identified - softening point (Ring and Ball), needle penetration and Fraass breaking point. The results of the tests are summarized in Table 1. It can be concluded that bitumen [R] did not meet the reference value of needle penetration and Fraass breaking point as the bitumen was too hard. The differences in the properties of bitumen [R] and [V] are minor but should be taken into account when interpreting the test results.

Table 1: Results of the tests on the two bitumen

		50/70 Venezuela [V]		50/70 Russia [R]	
		delivery	after RTFOT	delivery	after RTFOT
Softening point Ring and Ball [°C]	*reference value*	*46 - 54*	*$\Delta \leq 9$*	*46 - 54*	*$\Delta \leq 9$*
	actual value	48.6	53.0	51.8	56.4
Needle penetration [0,1 mm]	*reference value*	*50 - 70*	*$\Delta \geq 50$ %*	*50 - 70*	*$\Delta \geq 50$ %*
	actual value	53.4	35.0	44.2	31.2
Fraass breaking point [°C]	*reference value*	*≤ -8*	-	*≤ -8*	-
	actual value	-8 / -9	-	-6 / -6	-

2.4 Rolling Bottle Test (RBT)

The RBT according to DIN EN 12697-11 was carried out using the aggregate/bitumen combinations mentioned above. For the test samples of aggregate and bitumen with and without adhesion agents were used. The purpose of the test is to ensure for a high performance of the adhesion agents and to reveal possible problems regarding the susceptibility of the bitumen/aggregate combinations to stripping. In the test the surface coverage of the binder on the aggregates is determined after 6 hours of rolling and again after 24 hours. Figure 1 shows the surface coverage for the bitumen/aggregate combinations [GV0] to [DR1] investigated in this study. For the abbreviations [GV0] to [DR1] see section 2.1.

The test results after 6 hours of rolling only show a small positive impact of the adhesion agent. After 24 hours of rolling the impact of the adhesion agent is more obvious for all bitumen/aggregate combination. The surface coverage is now 11% higher for bitumen/aggregate mixes with biotite-granodiorite and still 4.5% higher for mixes with diabase.

A major disadvantage of the RBT is that only aggregate fractions from 8 to 11 mm can be investigated. The stripping behavior of larger and smaller aggregate sizes can only be estimated from the test results. According to the standards (DIN EN 12697-11) the test is to be conducted under wet conditions. It is widely known, that water infiltrates into the aggregates as well as into the binder changing their electrical charge, which in turn changes the adhesion between binder and aggregates.

2.5 Indirect Tensile Test (ITT)

The Indirect Tensile Strength Ratio (ITSR) according DIN EN 12697-12 is a common test result to rank asphalt mixtures according to their susceptibility to moisture. In this test the indirect tensile strength of dry specimen is compared with the indirect tensile strength of water saturated specimen after 72 hour storage in water at 40°C. The indirect tensile strength is determined at 15°C applying a constant deformation rate of 50 mm/min. The ITSR can be calculated using Equation (1).

$$\mathrm{ITSR} = \frac{\beta_{\mathrm{sat./stored}}}{\beta_{\mathrm{dry}}} \quad [\%] \tag{1}$$

wherein $\beta_{sat./stored}$ in [MPa] represents the indirect tensile strength at 15°C for water saturated specimen after 72 hours of storage in water at 40°C, and β_{dry} in [MPa] denotes the indirect tensile strength at 15°C.

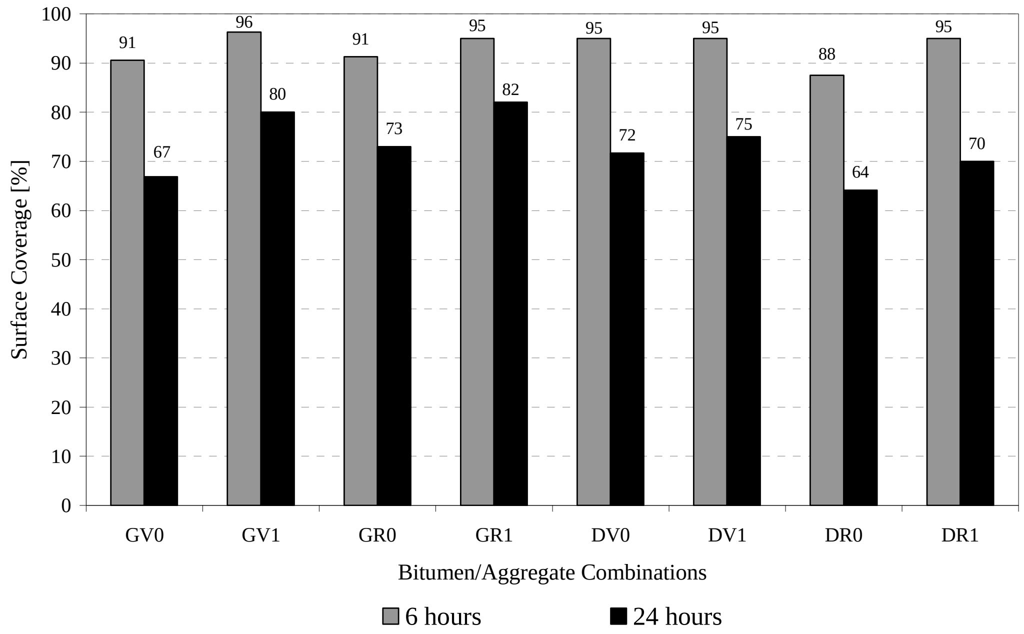

Figure 1: Surface Coverage of the aggregate/bitumen combinations after 6/24 hours of rolling

The water saturation was achieved through a

- (30 ± 5) min storage of the specimens in an exhausted and water filled vacuum desiccator at (20 ± 5)°C and at a residual pressure of (6.7 ± 0.3) kPa,
- slow reinstatement of the atmospheric pressure, and
- (30 ± 5) min storage of the specimens in the vacuum desiccator at atmosphere pressure.

With this procedure a saturation of about 65 to 69% was obtained. If the specimen is saturated the indirect tensile strength is to be interpreted as the net stress at failure. The net stress represents the combined stresses transferred through the mix and through the water. The stress transferred through the mix is generally called effective stress, while the stress that is being transferred through the water is called pore water pressure. Considering that under saturated or partly saturated conditions the mix as well as the pore water contributes to the load transfer it appears to be reasonable that in some cases ITSRs may be larger than 100% (Gubler et al. 2005, Vansteenkiste 2008). To fully understand the influences of the water on the failure stress $\beta_{sat./stored}$ it may be helpful to distinguish between chemical effects and hydraulic effects of the water. Due to the presence of water the strength of the mix is being reduced since the water reduces the adhesion between binder and aggregates. This is a chemical effect, which reduces $\beta_{sat./stored}$. The hydraulic effect originating from the contribution of the water to the load transfer increases the $\beta_{sat./stored}$ value. Three different stages of material behavior may now be identified; (A), the degree of saturation is at a level where the increase in $\beta_{sat./stored}$ due to the hydraulic effect exceeds the reduction in $\beta_{sat./stored}$ due to the chemical effect. At this level ITSRs are larger than 100%. (B), the degree of saturation has reached a value where the chemical effect and the hydraulic effect cancel each other out and the ITSRs equal 100%. (C), the degree of saturation is at a point such that the reduction in $\beta_{sat./stored}$ due to the chemical effect exceeds the increase in $\beta_{sat./stored}$ due to the hydraulic effect, which manifests itself by ITSRs smaller than 100%. The stages materials must be assigned to do not only depend on the degree of saturation but also on the chemical and hydraulic characteristics of the mixes. Therefore additional tests were performed on specimen which were water saturated and directly tested as well as specimen which were water saturated, stored 72 hours in water at 40°C and than dried 28 days at room temperature. The exposure conditions for the ITTs are listed below and Table 2 summarizes the test conditions used for the ITTs.

- dry – specimen conditioned for 4 hours at 15°C in a climate chamber
- saturated – specimen were water saturated (see above) and than conditioned for 4 hours at 15°C in a water bath
- water stored – specimen were water saturated, stored for 72 hours in water at 40°C and than conditioned for 4 hours at 15°C in a water bath
- water stored & dried – specimen were water saturated, stored 72 hours in water at 40°C, dried 28 days at room temperature and than conditioned for 4 hours at 15°C in a climate chamber (checking the specimen weight showed that even after 28 days residual water was in the specimen)

Table 2: Exposure conditions for the ITT and CITTs on the eight asphalt mixtures

Aggregate / Bitumen		Biotite-Granodiorite [G] or Diabase [D]			
		dry	saturated	water stored	water stored & dried
Venezuela	[V0]	▼ ▲	▼ ▲*	▼ ▲	▼ ▲
Venezuela with adhesion agent	[V1]	▼ ▲	▼ ▲*	▼ ▲	▼* ▲
Russia	[R0]	▼ ▲	▼	▼ ▲	▼* ▲
Russia with adhesion agent	[R1]	▼ ▲	▼*	▼ ▲	▼* ▲

▼ ITT ▲ CITT * only for biotite-granodiorite

The test results are displayed in Figure 2. The first column represents the defined ITSR according DIN EN 12697-12. The test results show a low ITSR value for saturated/water stored specimen. A high ITSR value can be observed for the dry/water stored & dried specimen, which is cause by a increased indirect tensile strength value as a result of the water storage (after treatment).

2.6 Cyclic Indirect Tensile Test (CITT)

Based on the test procedures mentioned above it is not possible to investigate the impact of adhesion agents and moisture on the fatigue life of asphalt mixtures. Since a deeper inside into the fatigue mechanisms of asphalt mixes is crucial for analytical pavement design processes Cyclic Indirect Tensile Tests (AL Sp-Asphalt 09) were performed considering the four different exposure conditions described before. Table 2 contains also the exposure conditions used for the CITTs.

26 different fatigue lines (based on 6 tests each – 3 different stress amplitudes, double realisation, see Table 2) were determined. In Figure 3 the numbers of load cycles to macro-crack formation is drawn vs. the initial elastic strain per cycle. The lines in Figure 3 represent test results on asphalt mixes at dry conditions. Based on the fatigue tests the asphalt mixes may be divided into two groups. The first group is formed by mixes using bitumen [R], while the second group is formed by mixes with bitumen [V]. The asphalt mixes with bitumen [R] exhibit better fatigue characteristics than mixes with binder [V]. No influence of the adhesion agent was found on the fatigue lines at dry conditions. Even after 72 hours storage in water at 40°C no clear influence on the fatigue lines can be observed.

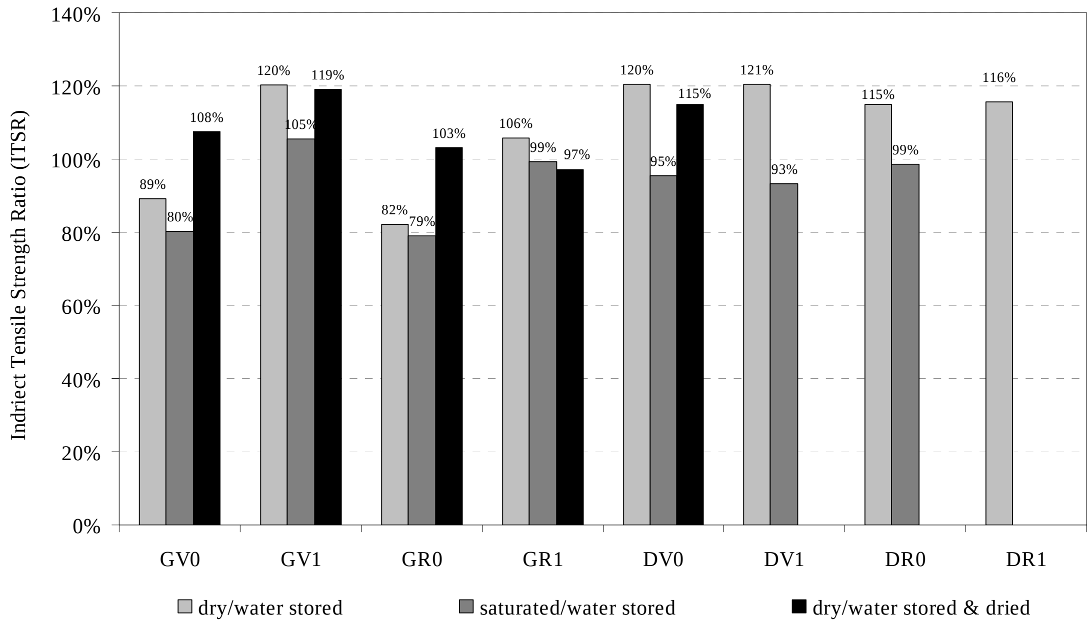

Figure 2: ITSR for different exposure conditions for the eight asphalt mixtures

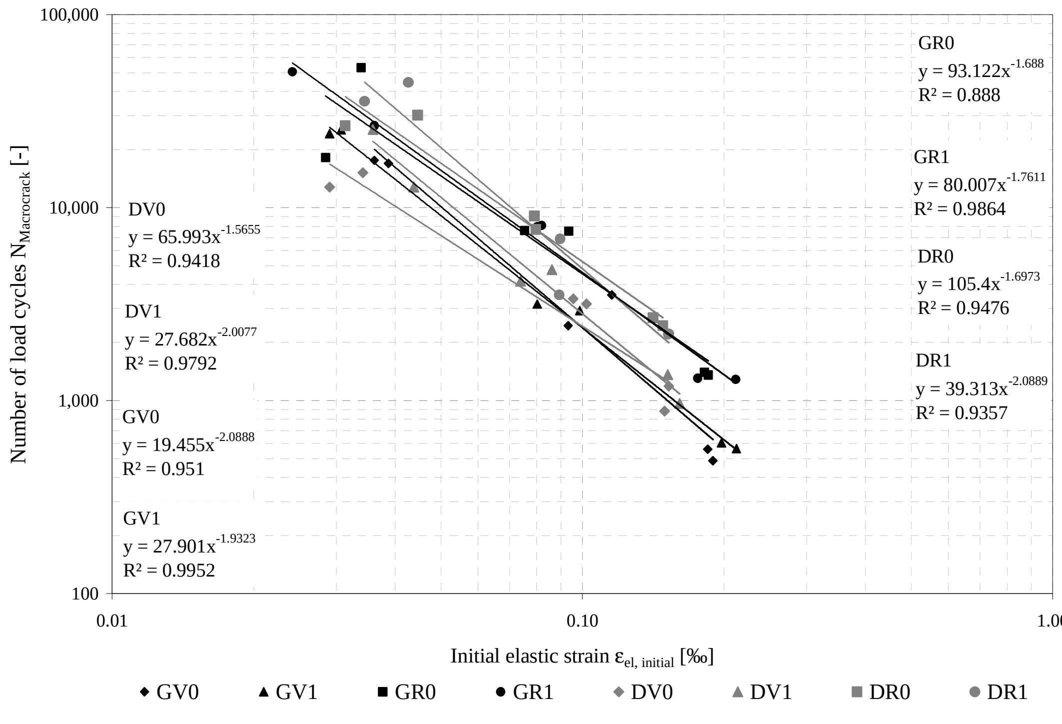

Figure 3: Fatigue lines of the eight asphalt mixtures – dry condition

In Figure 4 the fatigue lines of the different exposure conditions are presented for the [GV1] asphalt mix. The worst fatigue line was observed for the dry specimen. No difference was found between the fatigue lines of the saturated specimens and the water stored specimen. In this context it is interesting, that the highest stiffness modulus value |E| was observed for the saturated specimen. The decrease in the stiffness modulus during the 72 hour water storage is about 1,000 MPa or 700 MPa if the dry/dried specimens are considered. In contrast to this the indirect tensile strength was increased.

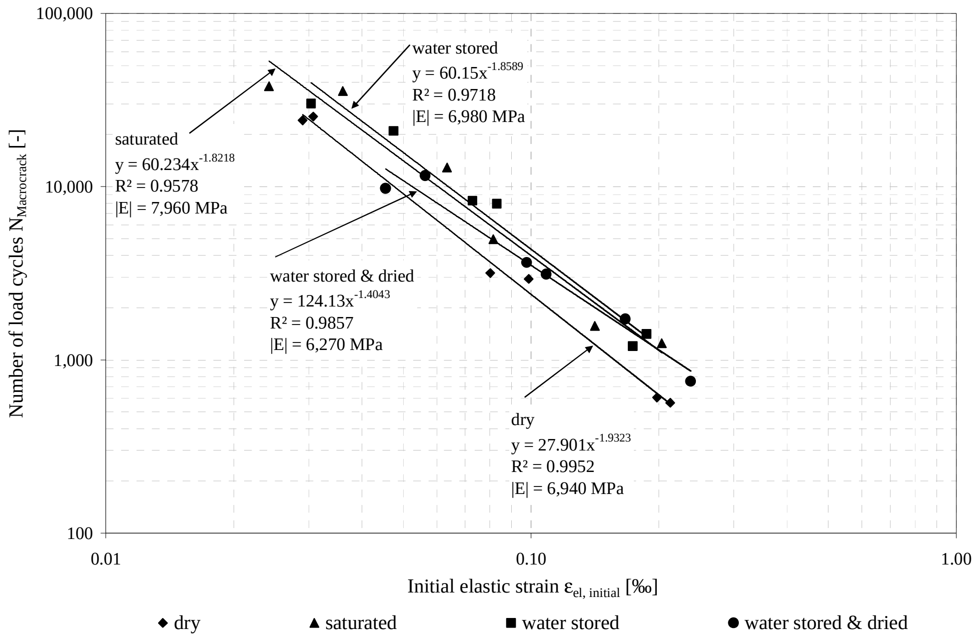

Figure 4: Fatigue lines for the [GV1] asphalt mix

3 IMPACT OF THE PORE WATER PRESSURE

Purpose of this section is to provide an explanation on the different behavior of the asphalt specimens when undergoing static and cyclic loading. For this reason a fully coupled 3-phase hydro-mechanical model will be used. With this model numerical studies will be carried out to investigate the effect of pore water under static and cyclic loading. In the model asphalts is considered as a three phase material consisting of solids, water and air. The water and the air phases exist independently from the solid grain skeleton.

3.1 Effective Stress

The overall stress σ_{ij} in the soil is given by

$$\sigma_{ij} = \sigma_{Sij} + \sigma_{Wij} + \sigma_{Aij} \tag{2}$$

wherein σ_{Sij} represents the effective stress transferred through the grain skeleton and σ_{Wij} and σ_{Aij} are the stresses in the water and the air phase. The effective stress may be determined with

$$\sigma_{Sij} = C_{SPijkl} \cdot \varepsilon_{kl} \tag{3}$$

wherein C_{SPijkl} represents the material tensor, ε_{kl} is the linear strain tensor. The material tensor depends on the elasticity modulus as well as on the Poisson's ratio. The contribution of the water phase to the load transfer is expressed by

$$\sigma_{Wij} = -\chi \cdot p_W \cdot \delta_{ij} \tag{4}$$

wherein p_W is the pore-pressure of the water phase and δ_{ij} is the Kronecker-Delta. Similarly, the contribution of the air phase is taken into consideration by

$$\sigma_{Aij} = -(1-\chi) \cdot p_A \cdot \delta_{ij} \tag{5}$$

wherein p_A is the pore-pressure of the air phase. The parameter χ denotes the effective stress parameter that governs the interaction between the solid and the water phase. The flow of water through the grain skeleton is described in the model using Darcy's law, which takes into consideration the pore pressure p_W, the permeability of the asphalt k_{Wij} in terms of the pore water flow as well as the viscosity of the water phase μ_W. The flow of the air phase can be described similarly to the flow of the water phase considering the permeability related to the air flow k_{Aij} and the viscosity of air μ_A. In order to use the flow models the compressibility of water and air must also be known. A detailed description of the model is given in (Oeser and Khalili 2009).

3.2 Numerical Studies

To investigate the effect of the pore water on the load transfer in the specimen the finite element model shown in Figure 5 has been used. Figure 5 shows only $1/8^{th}$ of the specimen. The specimen has a diameter of 100 mm and a thickness of 40 mm. The material parameters used for the analysis are given in Table 3.

A vertical load P was applied at point A (see Figure 5) and the horizontal elastic strain ε_h at point B as well as the horizontal elastic displacement v_h of point C were determined for a static loading as well as for a dynamic loading. The degree of saturation was 67%. The relationship (6) between the horizontal strain ε_h and the horizontal displacement v_h was found from the numerical simulations for the static load.

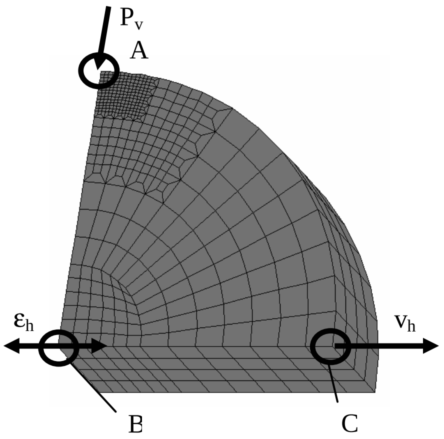

Figure 5: FE-Model

Table 3: Material Parameters

Poisson's ratio	0.267
Elasticity of asphalt	7,000,000 kPa
Compressibility of water	$4.700 \cdot 10^{-7}$ kPa^{-1}
Viscosity of water	$1.0 \cdot 10^{-6}$ s·kPa
Permeability (water flow)	$7.74 \cdot 10^{-6}$ m/s
Compressibility of air	$1.00 \cdot 10^{-2}$ kPa^{-1}
Viscosity of air	$1.7 \cdot 10^{-8}$ s·kPa
Permeability (air flow)	$3.55 \cdot 10^{-6}$ m/s
Saturation	0.67

$$\frac{\varepsilon_h}{2 \cdot v_h} = 21.11 \text{ m}^{-1} \tag{6}$$

The relationship recommended in most of the ITT standards to back calculate the horizontal strain ε_h at the centre of the specimen from the horizontal displacement v_h is given with equation (7).

$$\varepsilon_h = \frac{2 \cdot v_h \cdot (1 + 3 \cdot \nu)}{(0.2732 + \nu) \cdot \pi \cdot R} \tag{7}$$

In equation (7) ν represents the Poisson's ratio and R denotes the radius of the sample. If equation (7) is rearranged with respect to the ratio $\varepsilon_h/(2\cdot v_h)$ and if R is set to 0.05 m and a value of 0.267 is used for ν the following result is obtained:

$$\frac{\varepsilon_h}{2\cdot v_h}=\frac{(1+3\cdot\nu)}{(0.2732+\nu)\cdot\pi\cdot R}=21.225\ \text{m}^{-1} \tag{8}$$

Hence, for static loading the ratio between horizontal strain and horizontal displacement determined in the numerical simulation is in line with the standards. Since the equations in the standards are based on drained conditions this, in turn, means that in the static case the pore water does not significantly contribute to the load transfer in the sample. The insignificant contribution of the pore water is explainable by the small load ratio and long load duration in the static test during which the pore water can drain out of the pores. For dynamic loadings the pore water can not drain away from the pores. In this case the numerical simulation yields a ratio between the horizontal strain ε_h at B and the horizontal displacement v_h at C of:

$$\frac{\varepsilon_h}{2\cdot v_h}=19.15\,\text{m}^{-1} \tag{9}$$

The numerical simulation also indicate that the horizontal strain ε_h for partly saturated conditions (degree of saturation was 67% in this study) is about 10% lower than the horizontal strains determined under drained conditions related to the same horizontal deformation v_h.

The deformation v_h is measured during the tests and eh is back calculated using equation (9). The consideration of the differences of the deformations and strains caused by the water filled pore space leads to the adjusted fatigue lines. Figure 6 shows also the adjusted fatigue lines for the [GV1] mix (marked with *). A parallel translation can be observed because only the initial elastic strain was recalculated (about 10% lower). In comparison to Figure 4 the fatigue lines of the different exposure conditions move clearly together.

4 DISCUSSION AND CONCLUSION

In this paper the strength and fatigue characteristics of different asphalt mixes with and without adhesion agent were investigated under different moisture conditions. Using an adhesion agent does not have any impact on the fatigue life under dry test condition. Further the effects of the pore water on the mechanical characteristics of the test samples were studies. The research has shown that equation (7) can not be used when the material is fully or partly saturated and dynamic loading is applied. This also partly explains the unexpected order of the fatigue lines in Figure 4. Intensive experimental and numerical research needs to be conducted to find true relationships between the horizontal strains ε_h at the centre of the specimen and the horizontal displacements v_h for fully or partly saturated conditions. The current practice (using equation (7) no matter if the material is saturated or not) may leads to wrong results and needs to be updated. The research has shown that no clear coherency between the test results of the different tests (RBT, ITT and CITT) exists because of the different loading during the test or the conditioning.

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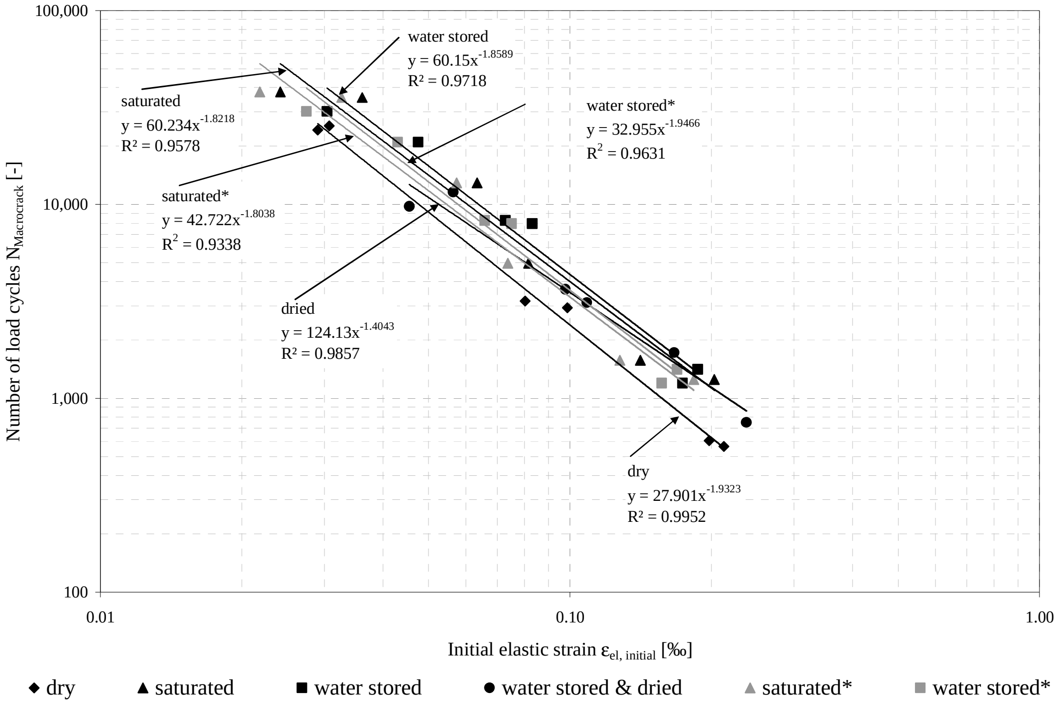

Figure 6: Fatigue lines for the [GV1] asphalt mix (* consideration of the pore water pressure)

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