



# Laboratory method to simulate short-term aging of hot mix asphalt in hydraulic engineering



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## HIGHLIGHTS

- Increased durability of an asphalt sealing element by minimizing the short-term aging.
- Optimization of the construction process due to appropriate lab simulations (HMAAT).
- Influences of long material hauling times on the bitumen characteristics.

## ARTICLE INFO

### Article history:

Received 15 March 2017

Received in revised form 9 May 2017

Accepted 26 May 2017

### Keywords:

Short-term aging

Thermal and oxidative aging

Asphalt mix

Bitumen

Hydraulic engineering

Asphalt sealing element

Extended material hauling times

## ABSTRACT

Asphalt sealing elements for dams have to be watertight and able to absorb strains without suffering from cracking and thus losing their sealing ability. As an effect of the aging process, bitumen becomes stiffer and more brittle accompanied by a deterioration of the asphalt flexibility. Construction sites in hydraulic engineering are in many cases in remoted areas. This leads to extended material hauling times and strong short-term aging effects. This paper presents a newly developed short-term lab-aging procedure (HMAAT – Hot Mix Asphalt Aging Test) to assess the changing of the material characteristics as a consequence of extended material hauling times and related high mix temperatures.

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## 1. Introduction

The desired performance characteristics of asphalt mixtures used for hydraulic engineering (e.g. highly flexible etc.) deteriorate during its service-life by thermal and oxidative processes. The entire process is summarized by the term aging ( $A_{TOTAL}$ ). The asphalt mix is composed of a mixture of bitumen, filler and aggregates, wherein the aging behavior of bitumen depends for a major part on the deterioration of the performance characteristics during the production process and in-service life. Aging is divided into short-term ( $A_{STA}$ ) and into long-term ( $A_{LTA}$ ) aging. The  $A_{STA}$  includes the manufacturing process of the mixed material, transportation and the placement. The  $A_{LTA}$  describes the aging process while in-service.  $A_{STA}$  is triggered by fast oxidation due to high temperatures and a high specific surface contacting oxidant agents during the mixing process, as well as the evaporation of the

remaining volatile components from the bitumen [1].  $A_{LTA}$  is driven by slow oxidation especially in the upper pavement layers by atmospheric oxygen and other highly oxidant gases (ROS – reactive oxidative species) available in the field [2–4]. All aging processes are irreversible and cumulative.

### 1.1. Asphalt sealing elements for dams

Rock fill dams with asphalt sealing elements are divided in two main types, asphalt faced rock fill dams (AFRD) and asphalt-core rock fill dams (ACRD). The material (asphalt concrete - AC) of both sealing types undergoes the same short-term aging influences during the construction but the long-term aging effects while in operation, which are mainly driven by the yield of ROS (e.g.  $NO_x$ ,  $O_3$ , OH-radicals, UV-radiation etc.) depend on the type and related location (on or in the dam body) of the asphalt sealing element (see Fig. 1). Asphalt concrete facings (AF) of permanent impounded reservoirs have reduced long-term aging rates compared to AFs with highly fluctuating reservoir water levels due to the time dur-

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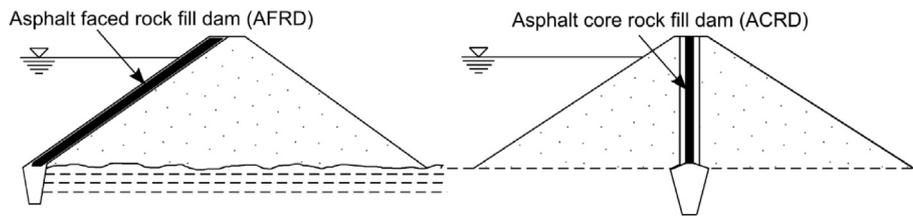


Fig. 1. Types of asphalt sealing elements, left: asphalt facing (AFRD), right: asphalt concrete core (ACRD).

ing water covers the sealing (e.g. amount of ROS in water is lower than in the air, protection against UV-radiation etc.). In addition, mechanical effects (e.g. scratches of drifting gravel-ice mixes etc.) which can have a negative impact on the long-term behavior must be considered in mountainous regions. Asphalt concrete cores (ACRD) have a decelerated long-term aging rate compared to AFs due to the protection of the asphalt concrete core against an over-supply of ROS and other harmful chemical and mechanical influences by the dam fill material.

### 1.2. Impact of the construction on the aging process

As an effect of the aging process, the bitumen becomes stiffer and more brittle accompanied by a deterioration of the asphalt flexibility. The main aim during the construction process of asphalt concrete facings and asphalt concrete cores is to obtain a highly flexible and water tight sealing element. To achieve the water tightness, the air void content after compaction must be lower than 3% by volume [5]. The temperature-dependent viscosity of the bitumen is a major influencing factor in the compaction process of the hot asphalt. Table 1 depicts minimum temperatures for placing and compaction in hydraulic engineering.

In order to guarantee the required minimum specific compaction temperature, the mixing temperature must be selected according to the cooling of the HMA (Hot Mix Asphalt) during the transportation and placing considering also the maximum allowable temperature of the bitumen brand. The remote construction sites in hydraulic engineering can lead to material manipulation times between 60 and 210 min and can be associated with high mixing temperatures (180–195 °C). Asphalt concrete facings and cores for dams and canals must be able to absorb strains without developing cracks. The aging effects of bitumen are the major factors influencing and changing the asphalt flexibility. With the deterioration of the flexibility behavior, the risk of cracking and leakage under stress increases. Investigations on bitumen samples in various production steps (mixing, transportation and placing) and after longer operation periods have shown that a crucial part of the deterioration of the good performance characteristics of asphalt occurs during the production process [6,7].

### 1.3. Simulation of short-term aging in the lab

In order to take the mentioned circumstances in Section 1.2 at the time of the suitability tests into account (mix design), it is important to be able to assess the bitumen aging in the lab as precisely as possible. The RTFOT [8] and the pressure aging vessel test

[9] are standardized and widely accepted as methods to transfer virgin bitumen into the state of  $A_{STA}$  (RTFOT) and  $A_{LTA}$  (RTFOT & PAV) [10–13]. Both tests are designed to simulate the aging process of bitumen (asphalt) for road construction under the typical influences. As previously mentioned, construction sites in hydraulic engineering have different asphalt requirements related to  $A_{STA}$  due to exposure and the associated material manipulation times. As a consequence of deviating requirements (hot material manipulation time) no satisfactory short-term aging forecasts in hydraulic engineering could be done for extended material manipulation times (>75 min) with the RTFOT for HMA. These circumstances resulted in the development of a necessary and appropriate  $A_{STA}$  laboratory test which also considers long material manipulation times and related high mixing temperatures. With the new  $A_{STA}$  – HMAAT (Hot Mix Asphalt Aging Test) the change of the bitumen characteristics during the manufacturing process can be simulated depending on the site exposure and associated material manipulation times as well as related temperatures. By applying HMAAT according to the most suitable bitumen types, appropriate site equipment (e.g. type of truck – conventional or thermo isolated etc.) and the maximum transportation time can be determined for each site condition. The HMAA-Test leads to an increased durability and a better long-term behavior of the asphalt sealing elements.

## 2. Materials and test methods

### 2.1. Materials

For the presented study, a standard asphalt concrete mix design commonly used in hydraulic engineering with a maximum nominal aggregated size of 11 mm (AC 11) was applied for tests. The coarse aggregates used for the mix consisted of limestone and the filler was powdered limestone (Fig. 2 displays the design grading curve for the investigations). The design grading curve was approximated to the Fuller curve ( $n = 0.45$ ) in order to achieve a low air void content and to ensure a good compactibility.

The content of the used modified bitumen (PmB) 45/80 – 65 was set to 6.7% by mass. The polymer-modified bitumen consists of bitumen 70/100 with a modification of 4.3 M.% SBS.

### 2.2. Specimen preparation

The mix (15 kg HMA for each test) was prepared in a laboratory reverse-rotation compulsory mixer, according to EN 12697-35 [14]. The mixing temperature for each test was selected depending on the experimental stage (see Table 3). The hot asphalt mix was transferred directly from the mixer into the test rig (Fig. 3). For bitumen analysis after aging in the HMAAT, bitumen was extracted according to EN 12697-3:2013 [15] with tetrachloroethylene ( $C_2Cl_4$ ) as a solvent. The solvent-bitumen solution was distilled according to EN 12697-3:2013 [15] to recover the bitumen.

Table 1  
Material temperature ranges for placing and compaction in hydraulic engineering [5].

	50/70	70/100	PmB
$T_{paver}$	150–180 °C	150–180 °C	150–180 °C
$T_{compaction}$	≥120 °C	≥120 °C	

\* Special requirements after suitability tests.

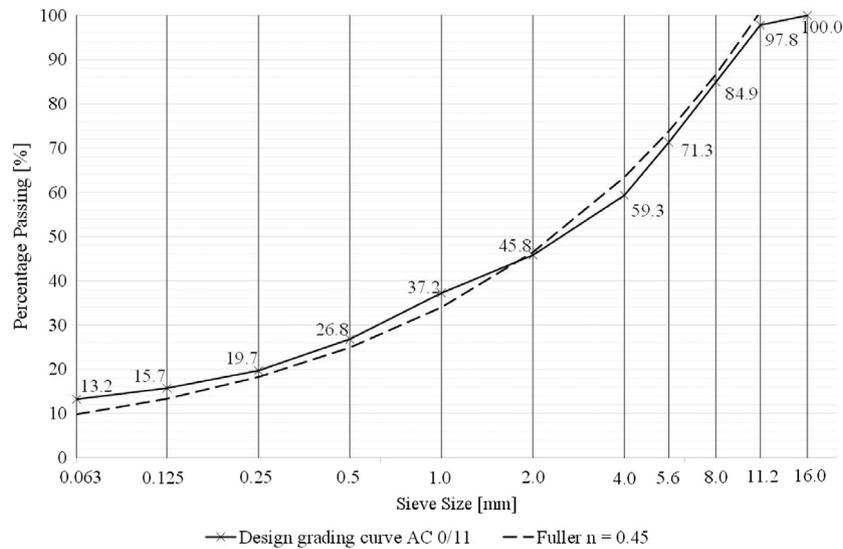


Fig. 2. Design grading curve AC 0/11 and Fuller curve ( $n = 0.45$ ).

Table 2

Main characteristics (mean values) of PmB.

Parameter	PmB 45/80–65
Penetration [1/10 mm]	66
Softening Point Ring & Ball [°C]	82.6
Elastic recovery [%]	96

Table 3

Experimental procedure.

	t = 60 min	t = 120 min	t = 210 min
$T_{\text{const}}$	$160 \pm 3$ °C (V1)	$160 \pm 3$ °C (V2)	$160 \pm 3$ °C (V3)
$T_{\text{variable}}$	$170.5 \pm 3$ °C (V4)	$178.5 \pm 3$ °C (V5)	$190 \pm 3$ °C (V6)

### 2.3. Short-term aging process in the test rig

Fig. 3 displays the developed test set-up and equipment for the simulation of the short-term aging process. A major part of the  $A_{\text{STA}}$  in the field occurs while the bitumen is mixed with aggregates (HMA). Due to realistic simulations of the specific surface area of the bitumen for chemical and physical aging processes (reactions), a mixed material aging test is more appropriately reflecting real aging conditions on site compared to a bitumen-aging test (e.g. RTFOT etc.). The aging process due to interactions between the bitumen and the aggregates are taken into account. The test setup allows a uniform through-flow of the material with the lowest possible energy expenditure while avoiding a heat accumulation under the HMA. A digitally controlled hot air blower provides a constant air volume flow for each test and the deflector ensures a uniform air distribution. A slight overpressure forces the air to flow through the perforated basket and the HMA and due to the perfect fit, the air cannot pass the basket outside. During the material manipulation on site, different reloads and related material mixing processes occur (mixing plant – truck, truck – paver). These steps lead to an acceleration of the aging process, on the one hand due to the increase of specific surface area of the bitumen, and on the other hand of an oversupply of ROS. In order to represent these processes during the  $A_{\text{STA}}$  tests, a constant oversupply of ROS due to the air volume flow through the HMA (400 l/min) is assured with the short-term aging apparatus. Temperature beneath, in and above the HMA can be controlled by digital temperature sen-

sors. All measured signals during an  $A_{\text{STA}}$  test are transmitted in real time to a computer. Various  $A_{\text{STA}}$  processes related to the HMA manipulation times and linked temperature ranges on site can be simulated in the lab. By applying air and a higher temperature in the HMAAT, the lab-aged HMA is more similar to the field-aged HMA under actual construction conditions.

### 3. Experimental program

In order to optimize the construction process in the field related to the aging effects ( $A_{\text{STA}}$ ) in the lab test apparatus, it was important to analyze and differentiate the oxidative from the thermal impact on aging. For this purpose two separate experimental procedures were completed (V1–V3 and V4–V6). As a result of non-accelerated artificial aging processes in the HMAAT, the experimental times are depending on real material manipulation times of HMA in hydraulic engineering which are depicted in Table 3. For a comparison of the short-term aging test results in the HMAAT-rig with a common standard short-term aging method, RTFOTs were performed simultaneously with the same virgin bitumen. In order to describe and visualize the  $A_{\text{STA}}$  process and effects to the bitumen characteristics, various DSR (Dynamic Shear Rheometer) [16], PEN (Needle Penetration) [17] and ER (Elastic Recovery) [18] tests were performed after each test stage and compared.

#### 3.1. Experimental procedures

##### 3.1.1. $A_{\text{STA}}$ with a variation of experimental time on a constant temperature (V1–V3)

In each stage, the material had the same temperature ( $160 \pm 3$  °C) but the oxidation time increased from V1 to V3.

##### 3.1.2. $A_{\text{STA}}$ with a variation of experimental time and temperature (V4–V6)

The procedure had the same time steps as V1–V3 but included a variation of the start temperatures (see Table 3). The start temperature for each experimental stage was dependent on the minimal compaction temperature for the placing and the cooling of the HMA during material manipulation related to the site equipment and weather conditions. For all tests (V4–V6) an average cooling rate of 0.15 °C per minute was adopted. The rate simulated 20 °C

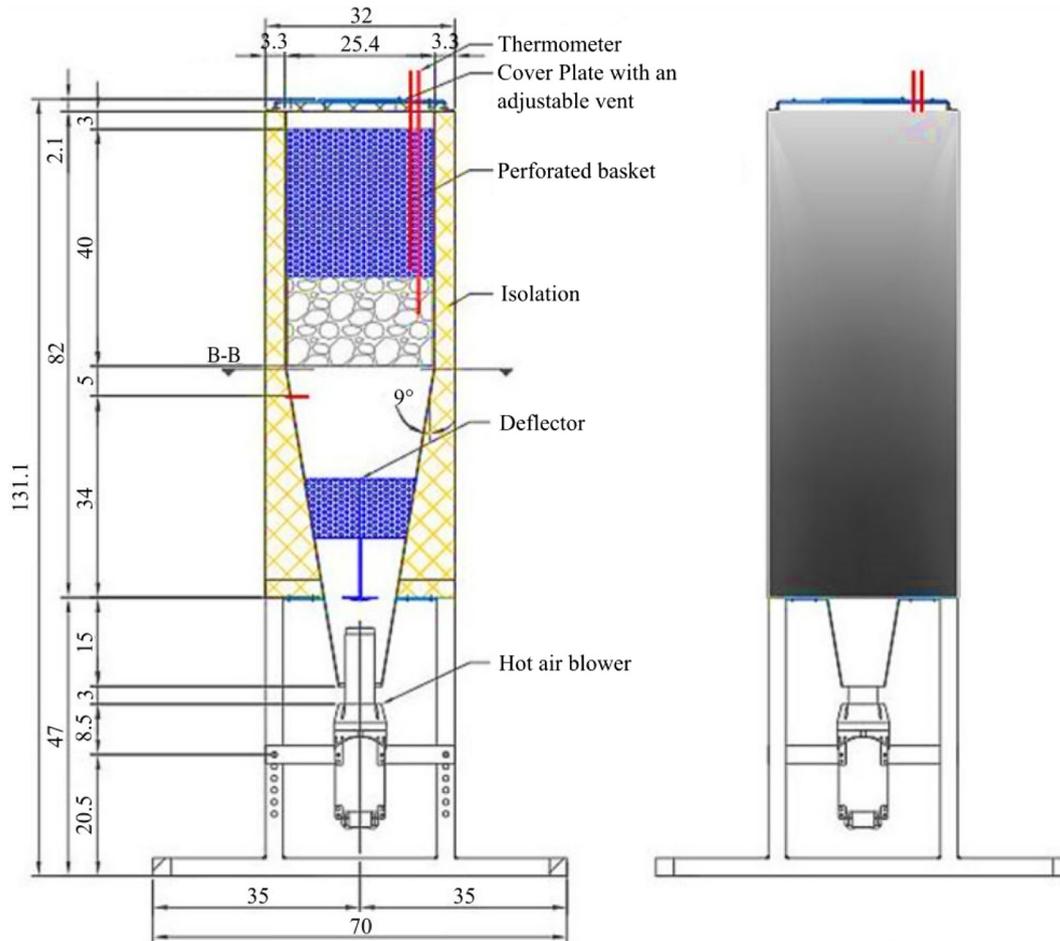


Fig. 3. Short-term aging – HMAAT – rig [6].

outside temperature, no wind, cloudy sky (no sun) and the use of thermo-isolated trucks. Due to the digital control of the hot air blower, the simulation of each cooling rate related to real site conditions (site equipment, weather etc.) can be regulated easily.

#### 4. Discussion and laboratory test results

##### 4.1. Impact of temperature and duration on aging

The HMA was prepared and tested in the HMAAT - rig under varying aging conditions (displayed in Table 3). Furthermore, DSR tests were carried out on all bitumen samples recovered from the lab-aged HMA specimens and from the virgin bitumen. The test procedure was chosen according to EN 14770:2005 [16] with a temperature sweep from +10 °C to +40 °C and frequencies between 0.1 and 10 Hz. The dynamic shear modulus  $|G^*|$  and the phase angle  $\varphi$  versus the frequency were determined. In addition the PEN and ER were conducted with conventional test methods (see Fig. 6).

The bitumen (see Table 2) selected for the present study was tested before and after aging in order to directly compare changes in its behavior due to HMAAT and RTFOT aging (see Fig. 4). Fig. 5 illustrates the DSR results as ratios between  $G^*(\text{aged})$  and  $G^*(\text{virgin})$ , Fig. 5a shows results from tests with a constant temperature (V1-V3) and Fig. 5b shows test results with increasing temperature (V4-V6) as a function of the material manipulation time (see Table 3). Fig. 5a shows an increase of  $G^*$  with extended oxidation time. Fig. 5b displays an increase of  $G^*$  between V4 and V5 and a slight decrease from V5 to V6. The stiffness reduction between

V5 and V6 can be explained as a combination of the embrittlement of the base bitumen and a molecule degradation of the SBS polymer. The main cause was most likely the high starting temperature ( $190 \pm 3$  °C) of the experimental stage (V6) and not the oxidation time. Material investigations (PEN and ER) support this thesis and are illustrated in Fig. 6 (cp. DSR data at 25 °C with PEN and ER data).

The results with a constant test temperature (V1-V3) in Fig. 5 and Fig. 6 indicate the time-depending aging process. This process continues until a shortage of ROS occurs. In order to accelerate the chemical reaction and the associated aging process once more, the temperature must be raised. The temperature impact on the aging process can be seen in Fig. 6a (comparison of V1/V4, V2/V5 and V3/V6). The best approximation of the RTFOT results in relation to the stiffness ( $G^*$ ) achieved in Fig. 5a, test stage V2 and in Fig. 5b experimental stage V4. This confirms that the RTFOT is suitable for the simulation of  $A_{STA}$  for material manipulation time's  $\leq 75$  min.

Fig. 7 shows the ratios between phase angles (aged) and phase angles (virgin) and depicts the changing of the phase angle ( $\varphi$ ) of the recovered bitumen specimens (HMAAT and RTFOT) versus the virgin binder during the aging. Fig. 7a shows a progressive decrease of ( $\varphi$ ) with increasing experimental time. However, the experimental stages V5 and V6 in Fig. 7b show the interaction between the base bitumen and the polymer. The same effect (interaction base bitumen and molecule degradation) as displayed in Fig. 5b leads to a stagnation of the decrease of ( $\varphi$ ) (V5-V6). At a test temperature of 25 °C the DSR data for  $G^*$  and  $\varphi$  corresponds with the other performed tests in this study.

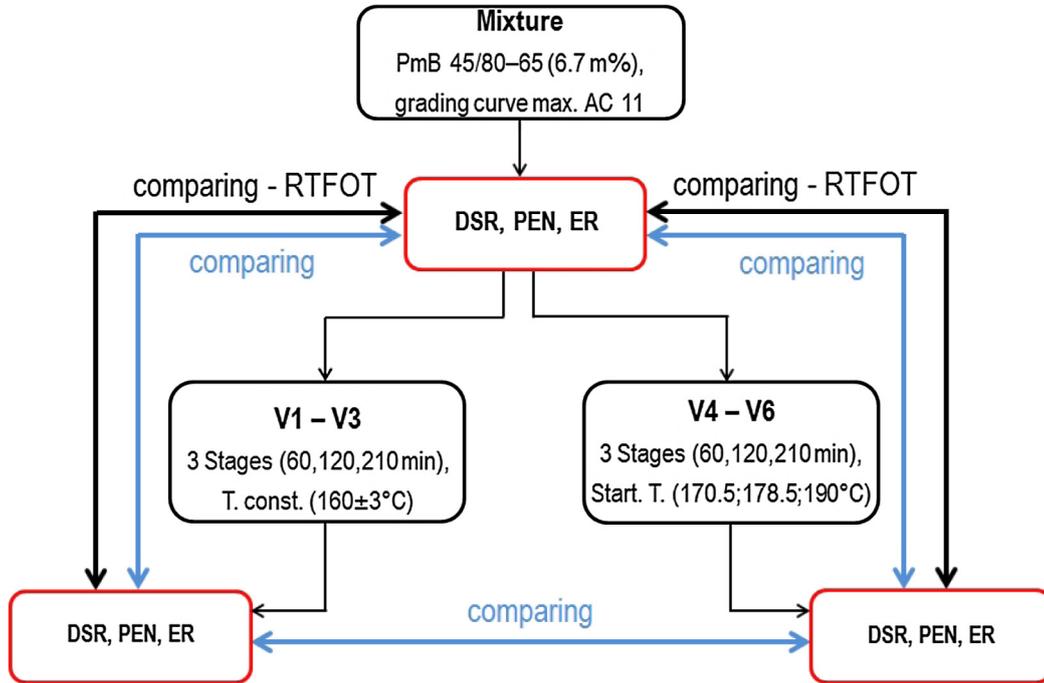


Fig. 4. Experimental program.

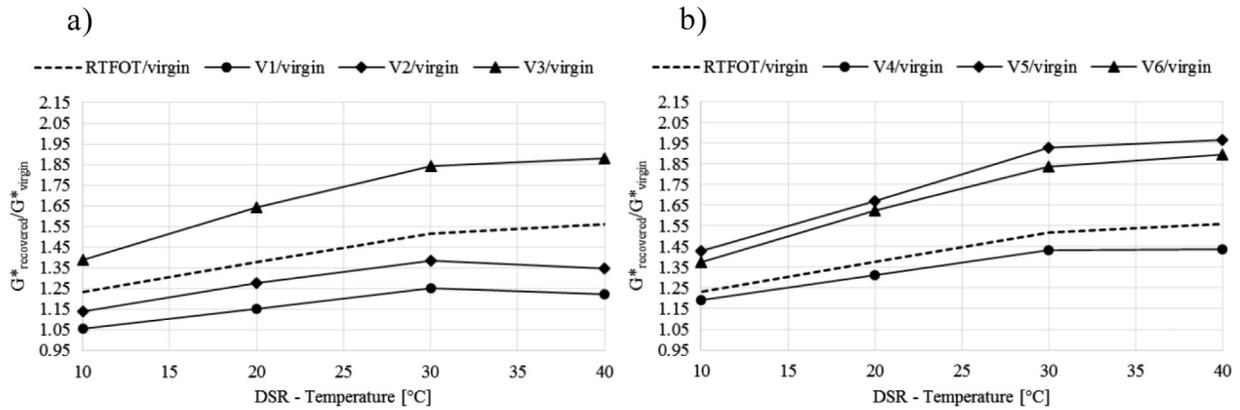


Fig. 5. Change in dynamic shear modulus ( $G^*$  - ratios are shown); V1-V6, RTFOT;  $f = 1.6$  Hz.

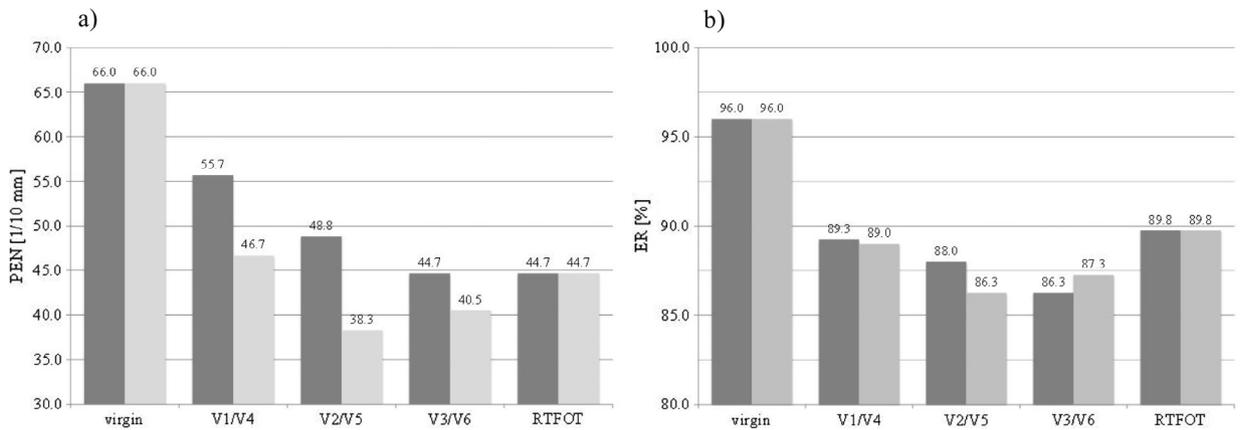


Fig. 6. (a) PEN, (b) ER; the data in the diagram are mean values.

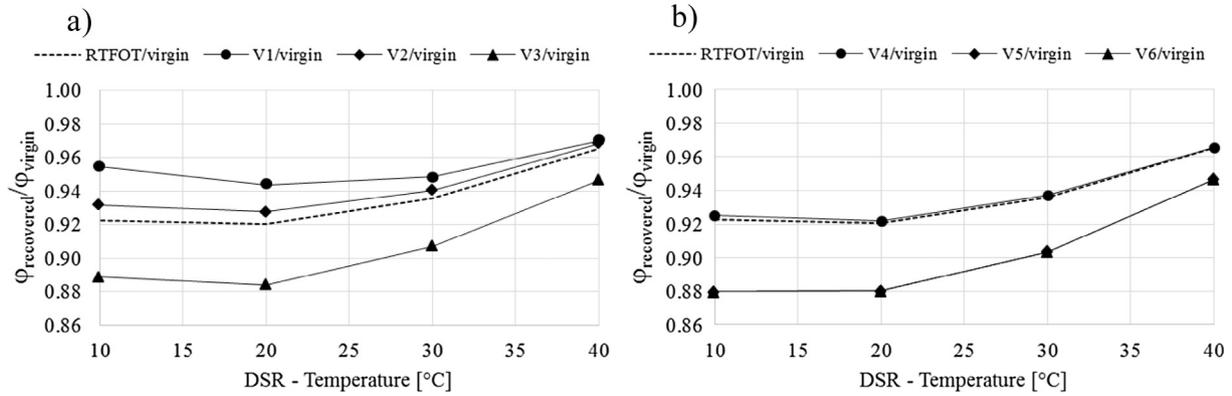


Fig. 7. Ratios between phase angles (aged) and phase angles (virgin); V1-V6, RTFOT;  $f = 1.6$  Hz.

4.2. Repeatability and accuracy

For a preliminary analysis related to the repeatability and accuracy of the HMAAT test for HMA in hydraulic engineering, three aging tests for each oxidation stage were performed. The displayed needle penetration test results in Fig. 8 show a high repeatability for the tested polymer modified bitumen in each experimental stage. The highest value of the standard deviation has V1 with 3.2%. This indicates a good repeatability.

4.3. Conclusion

The primary purpose for the research project presented within this paper was to develop an efficient  $A_{STA}$  method for HMA in hydraulic engineering for the estimation and assessment of the long-term performance during the mix design suitability tests. The presented aging test procedure is based on the principle of a chimney pipe with a forced flow of air through the specimen at different temperature levels. The tests can be done exactly with the same temperatures and aging times which occur at the construction site. In case of long material hauling and transportation times, the RTFOT is difficult to apply for an  $A_{STA}$  estimation. The RTFOT method should only be used for specific site conditions with short hauling times of less than approximately 60 min. The main advantage of the HMAAT short-term aging method is that the majority of different impacts related to the material manipulation time can be reproduced realistically by the lab simulation. Due to this circumstance it is possible to combine the mix design and mix temperature with the logistic at the site. It seems important to keep the temperatures as close to the field conditions as possible in order to prevent any artificial chemical reactions that otherwise would not occur in the field. The constant air flow in the test rig can simulate the air entrainment in the material during transportation, reloading and placing. Bitumen was extracted and recovered from all lab aged HMA specimens and DSR, PEN and ER tests were performed in order to investigate changes in the bitumen behavior and compare the changes to virgin binder samples. Correlations were found between the  $A_{STA}$  aging with the RTFOT and the HMAAT depending on different experimental stages. The experiments with constant temperature ( $160 \pm 3$  °C, V1-V3) generally showed a decrease in aging speed with an increase in experimental time. This can be explained by the reduction of the ROS with an increasing experimental time. Due to the low temperatures (V1-V5), the polymer and the characteristic to restore the elastic properties while cooling was not damaged or only slightly damaged during the aging process. The experimental stages V4-V6 displayed the high influence of temperature over 170 °C to the performance characteristics of the bitumen.

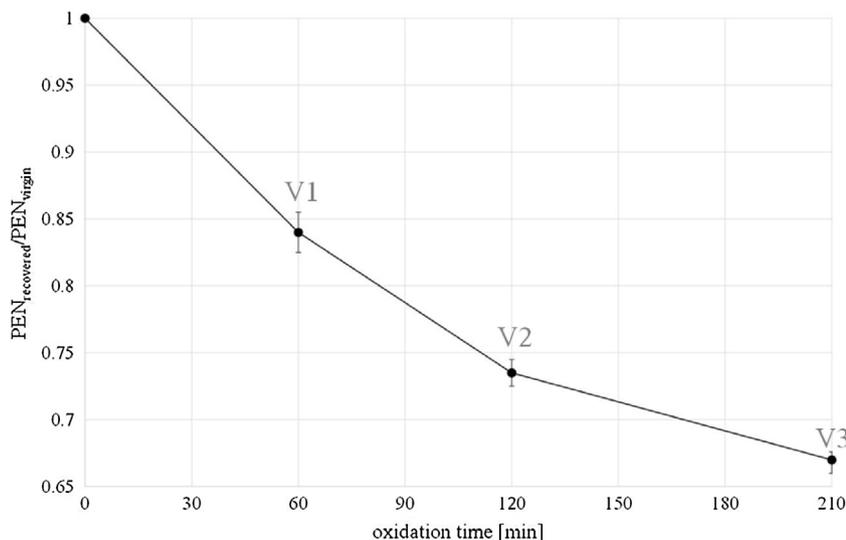


Fig. 8. Change in PEN of recovered bitumen from HMAAT aged specimens compared to virgin bitumen samples.

#### 4.4. Application advantages resulting of the HMAAT

Because the HMAAT can be flexibly adapted to various site conditions, the following advantages can help to avoid strong short-term aging effects during the construction stage:

- Estimation of the maximum material manipulation time and related temperatures (distance between mixing plant and construction site).
- Knowledge of interactions (compatibility) between bitumen and the aggregates during the construction process.

The before mentioned advantages can help in the selection of:

- the optimal bitumen pertaining to the material embrittlement during the construction process
- the bitumen type (modified or non-modified)
- site equipment (conventional truck, thermal-insulated truck e.g.).

#### 4.5. Further research

The results presented in this paper are encouraging for further research on the HMAAT for HMA in hydraulic engineering to gain additional knowledge about the impacts of aging of bitumen. Further research should be continued as follows:

- Comparison of the aging conditions of the laboratory experiments with those from the construction sites for different cases
- Determination of the influence of the bitumen embrittlement on the flexibility of asphalt concrete facings.
- Comparison of the  $A_{STA}$  behavior of modified and non-modified bitumen and the resulting influences on the long-term behavior of asphalt concrete facings.

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