Relationship between the production process and the long-term behavior of asphalt facings on rock-fill dams (AFRD)

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ABSTRACT

Asphalt facings on rock-fill dams (AFRD) 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. The aging process is divided into short-term (ASTA) and long-term (ALTA) aging. Investigations have shown that a crucial part of the deterioration of the good performance characteristics occur while ASTA. To increase the durability of asphalt facings it is important to minimize these aging effects during the construction process. 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 caused by high mix temperatures. This paper presents a newly developed short-term lab-aging procedure (HMAAT - Hot Mixed Asphalt Aging Test) to assess the change of the material characteristics as a consequence of extended material hauling times and related high mix temperatures of the bitumen. The comparison of bitumen aging conditions of inventory data and artificial lab-aged bitumen samples presented in this paper confirms the crucial influence of the ASTA on the whole aging process (ATOTAL).

1. INTRODUCTION AND BACKGROUND

Well-designed and constructed asphalt facings on rock-fill dams (AFRD) possess good performance characteristics (stress relaxation, etc.). These good properties can be traced back to the material behavior of the asphalt concrete (hereinafter referred to as asphalt). Asphalt material is composed of a mixture of bitumen, filler and aggregates (Figure 1, left), wherein the aging behavior of bitumen depends for a crucial part on the deterioration of the asphalt performance characteristics during the production process and in-service life.

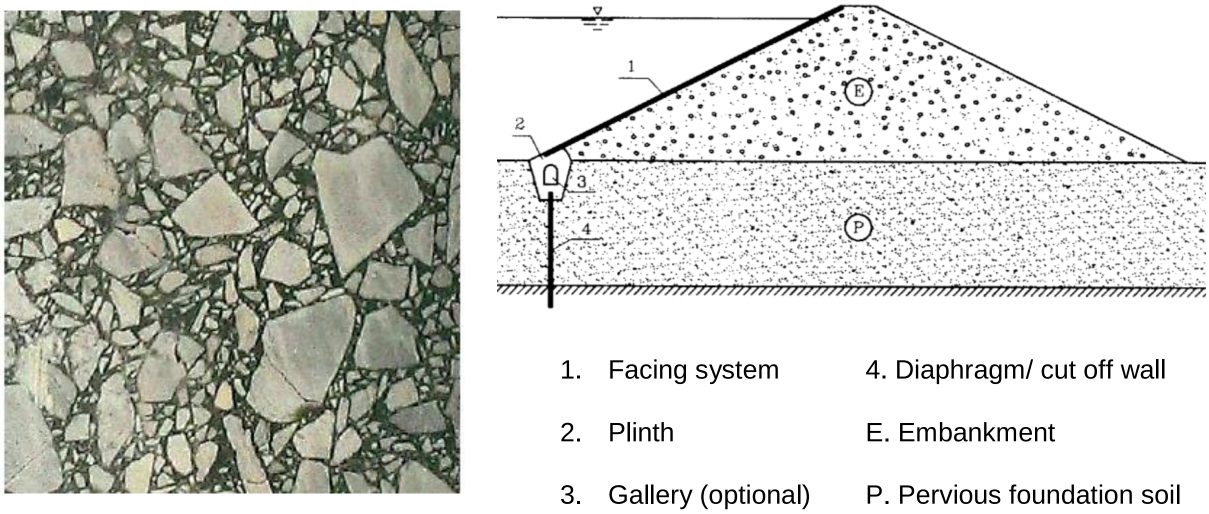


Figure 1. Left: Asphalt matrix (AC 0-11 mm, 6.7 M% Bitumen), Right: Water barrier system of an embankment dam with upstream asphalt concrete facing (AFRD), (ICOLD 1999)

The entire change in performance characteristics (material embrittlement and increase in stiffness) is summarized by the term aging (A_{TOTAL}).The aging process is divided into short-term (A_{STA}) and into long-term (A_{LTA}) aging. A_{STA} includes the production process of the mixed material, transportation and the placement. A_{LTA} describes the aging process while in-service. A_{STA} is triggered by fast oxidation due to high temperatures and high specific surface contacting oxidant agents during the mixing process, as well as the evaporation of the remaining volatile components from the bitumen (Petersen J.C. et al. 1994). A_{LTA} is driven by slow oxidation especially the upper pavement layers by atmospheric oxygen and other highly oxidant gases (ROS – reactive oxidative species) available in the field (Morian N. et al. 2011, Hofko B. et al. 2015 and Steiner D. et al. 2015). Depending on the penetration depth, ROS are divided into three groups (Figure 2).

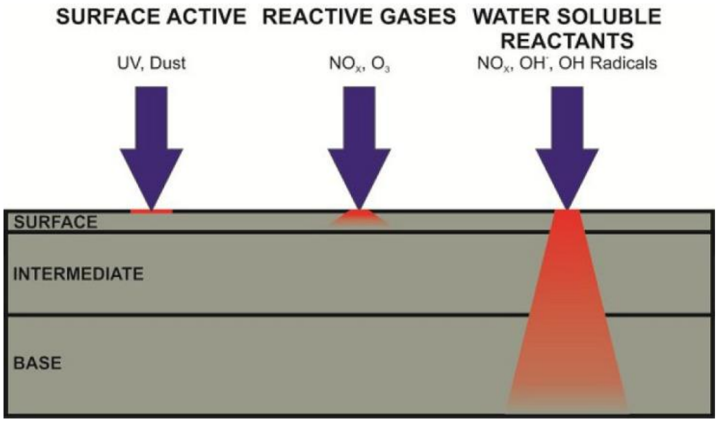


Figure 2. Grouping of oxidative and reactive agents regarding depth of penetration (Handle F. 2014)

Penetration depths shown in Figure 2 are only valid for undamaged (no cracks etc.) asphalt surfaces (Figure 3).

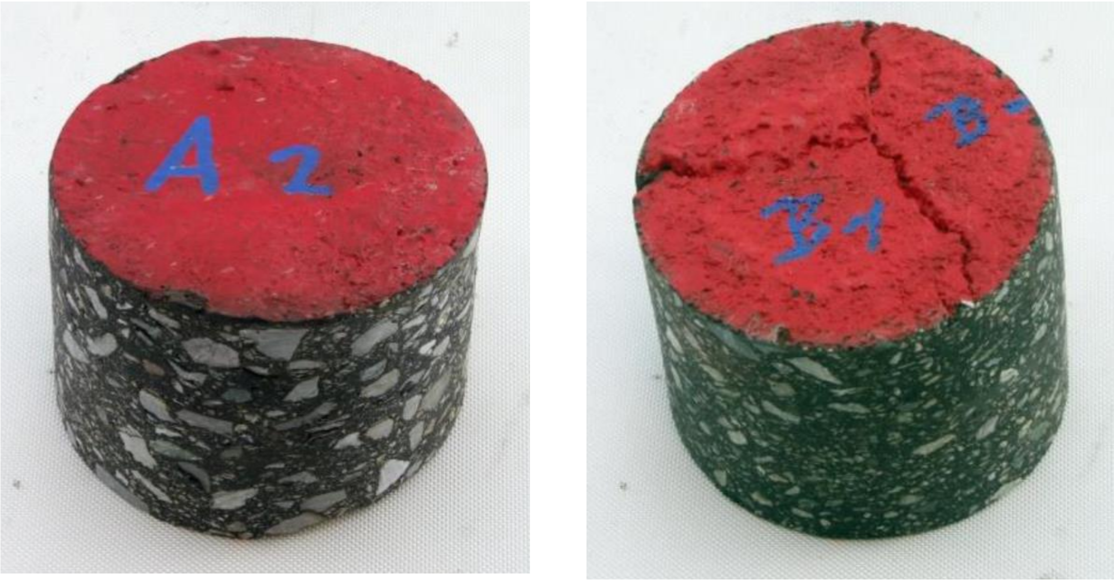


Figure 3. Left: Undamaged sealing surface, Right: Damaged sealing surface

Due to material embrittlement and increasing stiffness caused by aging processes, the surfaces of asphalt sealing elements can be damaged (cracks etc.) and ROS penetrate deeper into the asphalt matrix. This circumstance results in an irreversible and progressive aging process. As an effect of material aging, bitumen becomes stiffer and more brittle accompanied by a severe deterioration of asphalt flexibility. The change of bitumen performance characteristics can be described by the change of the material viscosity. The horizontally red dashed line in Figure 4 depicts the intrinsic viscosity. If this material behavior is reached, the asphalt sealing element can no longer meet the required material properties like flexibility, low temperature performance, no cracking etc.

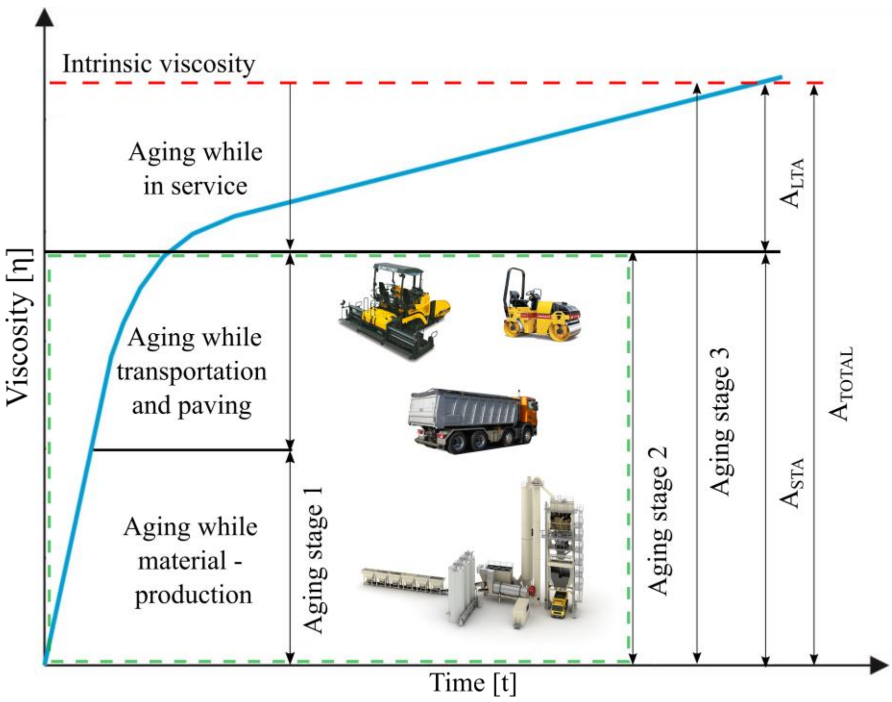


Figure 4. Asphalt aging process - changing of bitumen viscosity and aging conditions (Smesnik M. 2016)

The temperature-dependent viscosity of bitumen is a major influencing factor onto the asphalt compaction process. In order to achieve the required minimum material compaction temperature, the mixing temperature must be defined depending on the cooling of the HMA (Hot Mixed Asphalt) during the transportation and placing. Construction sites in hydraulic engineering are in many cases in remoted areas, this leads to material manipulation times between 60 and 180 minutes and higher mixing temperatures (approx. 180 – 195 °C). Aging effects of bitumen (material embrittlement and increase in stiffness) have a crucial impact on the deterioration of asphalt flexibility, hence the risk of cracking and leakage under stress increases. Investigations of bitumen samples in various production steps (mixing, transportation and placing) and in-service life have shown that a significant part of the deterioration of the performance characteristics of asphalt occurs during the production process. The main influence of A_{STA} is depicted in Figure 4 (green dashed box). The construction process of an asphalt-sealing element must be optimized as a result of the irreversible and cumulative short-term aging effects in order to improve durability and long-term behavior. For this purpose, a new test method was developed to simulate short-term aging and the resulting effects on asphalt characteristics already in the phase of the suitability tests. With the new A_{STA} – HMAAT (Hot Mixed Asphalt Aging Test) the change of bitumen characteristics during the production process can be simulated depending on the site exposure, the associated material manipulation times and related mixing temperatures. By applying HMAAT the most suitable bitumen types, appropriate site equipment and the maximum transportation time of the HMA can be determined for specific site conditions. This furthermore leads to a reduction of bitumen embrittlement during the construction stage (A_{STA}) and consequently to an increased durability and better long-term behavior of asphalt facings.

2. MATERIAL INVESTIGATIONS AND TEST METHODS

In order to prove the thesis that a crucial part of the aging process (A_{TOTAL}) occurs during the A_{STA} (see section 1 and Figure 4), results of bitumen investigations (values of needle penetration - PEN_{INDEX}) in various aging conditions were compared. While the influence of aggregates is negligible, the crucial part of the aging behavior is caused by bitumen. Several investigations have shown that the needle penetration test (conventional test method) according to EN 1426:2007 is suitable for determining the aging condition of non-modified bitumen. The basis therefore is the experimental geometry and the test procedure. Data sources used for the presented investigations in this paper are depicted in Table 1.

Table 1. Compilation of the data collective

Data source	Virgin bitumen (A)	A_{STA}	A_{TOTAL}
Inventory data from the construction period (A, field-aged)	X	X	
Investigation results of recovered bitumen of drill cores (field-aged, Figure 5)			X
Artificially short-term aged bitumen in the lab with HMAAT and RTFOT (CEN EN 12607-1 2007)	X	X	

For all bitumen analysis after aging in the field or in the lab, bitumen was extracted from the asphalt according to EN 12697-3:2013 with tetrachloroethylene (C_2CL_4) as a solvent. The solvent-bitumen solution was distilled according to EN 12697-3:2013 to recover the bitumen samples. Various investigations of the Institute of Transportation, Vienna University of Technology have shown that no significant change occurs in the bitumen performance characteristics during the recovery process according to EN 12697-3:2013.

Figure 5. Drill core extraction from an AFRD for bitumen recovery

2.1 Bitumen recovery from drill cores (A_{TOTAL})

The total thickness of the asphalt facing (core depth) was not used for bitumen recovery. The material aging rate (A_{LTA}) decreases with increasing asphalt cover (Zhengxing W et al. 2015). The reason is the shortage of ROS with increasing asphalt cover for chemical aging reactions (cp. section 1). In order to create representative asphalt samples for bitumen recovery the upper 15 mm of the cores were removed (Figure 6). The extracted bitumen of the core showed average aging conditions as a result of the aging distribution (aging rate) over the core depth. Due to the removal of the upper layer and the recovery of the bitumen from an undamaged sealing element layer (no cracks etc.), the error of averaging the aging conditions can be minimized. The test program and the required bitumen quantity for the determination of the aging of the bitumen should be defined in advance to minimize the height of the core layer for recovery. This procedure results in a reduction of errors in the statistical averaging.

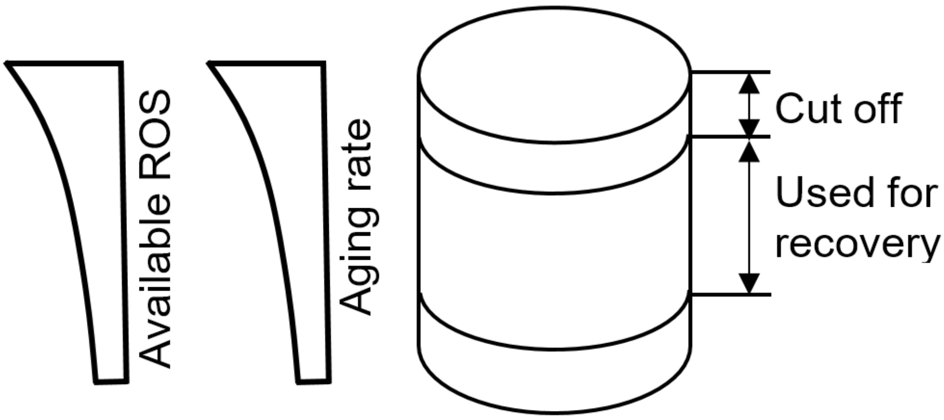


Figure 6. Drilled core, aging distribution over core height, used layer for recovery

2.2 Simulation of short-term aging in the lab

For a comparison of field-aged with lab-aged HMA, two different short-term lab-aging procedures were performed.

2.2.1 HMAAT – Hot Mixed Asphalt Aging Test

The HMAAT (Figure 7) was developed particularly to simulate the A_{STA} of HMA in hydraulic engineering (Smesnik M. 2016). A major part of the A_{STA} in the field occurs while bitumen is mixed with aggregates (HMA). In order to obtain realistic simulations of the specific surface area of the bitumen for chemical and physical aging processes, a mixed material aging test is a more appropriate reflection to real aging conditions on site compared to a bitumen-aging test (RTFOT). The effects on the aging process due to interactions between the bitumen and the aggregates are also taken into account. During material manipulations on site, different reloads (mixing plant – truck, truck – paver) and related material mixing processes will occur. This leads to an acceleration of the aging process, on the one hand due to the increased specific surface area of the bitumen, and on the other hand due to an oversupply of ROS. In order to represent these processes during short-term aging tests in the HMAAT, a constant oversupply of ROS is assured by an air volume flow through the HMA (400 l/min). Various A_{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.

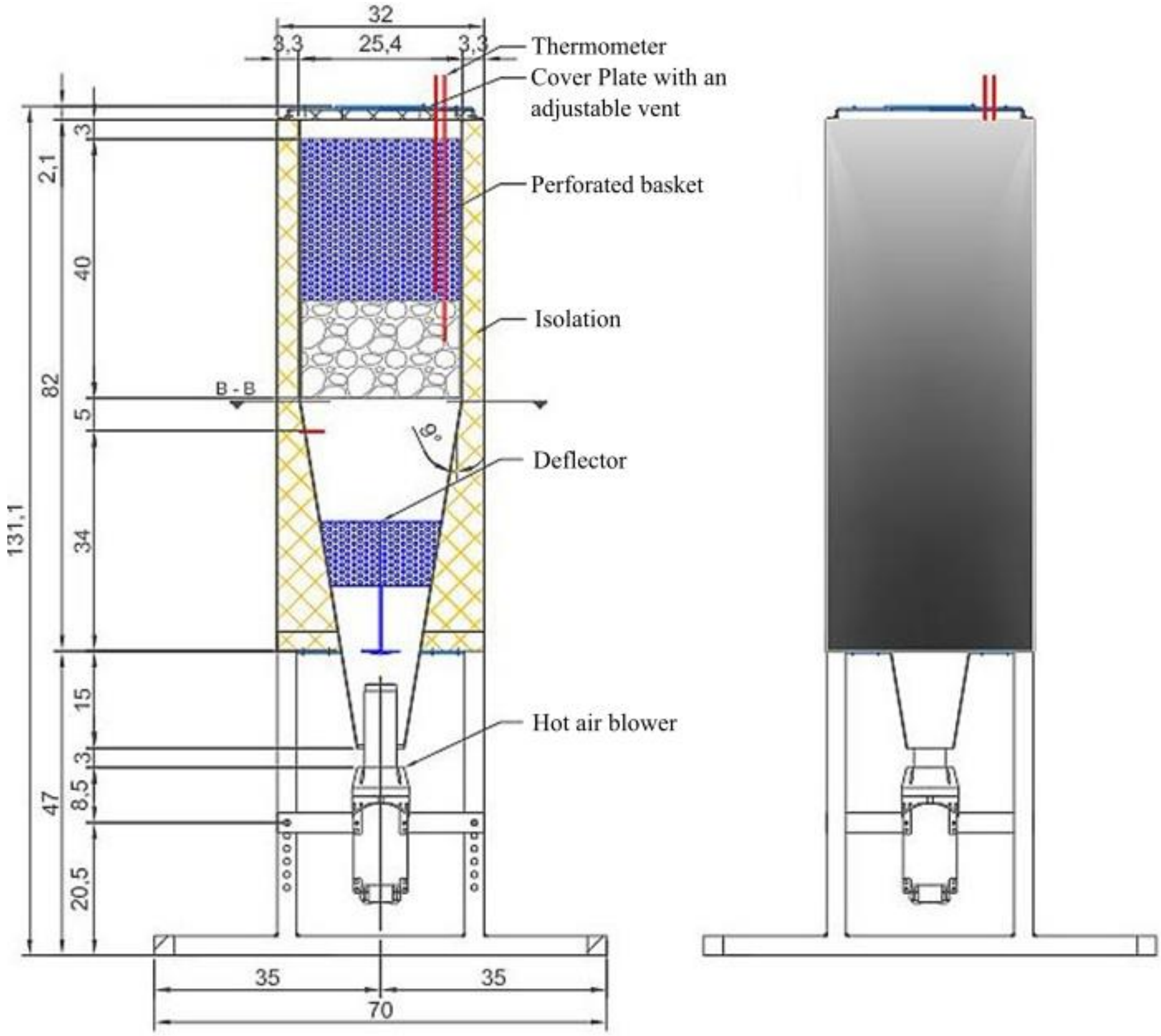


Figure 7. HMAAT - Test rig (Smesnik M. 2016)

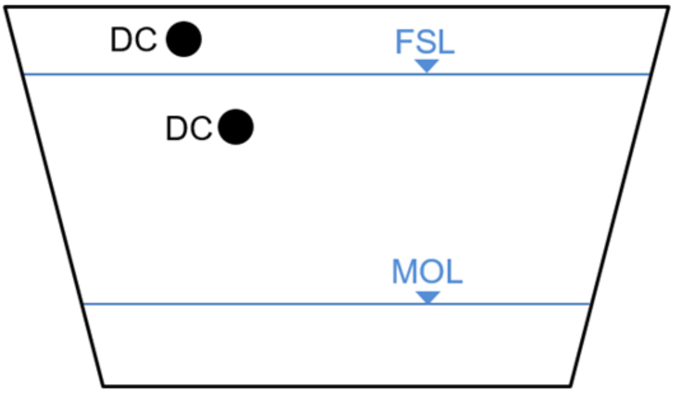
2.2.2 RTFOT – Rolling Thin Film Oven Test

As previously mentioned the RTFOT is a lab-test to simulate short-term aging of bitumen (Figure 8). This test was developed for the field of road construction to simulate short-term aging effects for material hauling times less than 75 minutes. Most construction sites in hydraulic engineering have different asphalt requirements related to A_{STA} due to the location in remote areas and the extended material manipulation times. As a consequence of deviating project conditions (hot material manipulation time etc.), no satisfactory short-term aging forecasts for HMA could be created for long material hauling times (more than 75 min.) with the RTFOT.

Figure 8. Rolling Thin Film Oven Test

3. COMPARISON OF FIELD-AGED WITH LAB-AGED HMA

Figure 10 displays the change of the needle penetration value (PEN) as indicator for performance characteristics of the bitumen in the asphalt. PEN results of the recovered bitumen taken from drilled cores (field-aged) of three well-documented asphalt facings on rock-fill dams with similar asphalt design are compared with the artificial lab-aged and recovered bitumen samples (HMAAT and RTFOT). Figure 9 illustrates the sampling method on the asphalt facings, one core above the full supply level (FSL) and one core below. Two cores were drilled in each of the three asphalt facings. By means of this method, a possible deviation of the aging conditions between the core sample above and below the FSL (amount of ROS in water versus ROS in air) was considered. The investigated material parameter PEN of the recovered bitumen from the middle part of the core displays no significant deviations related to the location of the cores taken below and above the FSL.



FSL… Full supply level

MOL… Minimum operating level

Figure 9. Method of drilled cores (DC) - sampling points on asphalt facings

The vertical axis in Figure 10 shows the penetration index ($PEN_{aged}/PEN_{(A)}$), the lower horizontal axis shows the time while in service and the upper horizontal axis displays the material manipulation time of the HMA during construction. The original bitumen types used during construction for the AFs are no longer available for laboratory simulations. The performance characteristics of the employed bitumen types for the lab simulations were similar to the characteristics in the field and normalized values of the needle penetration (PEN_{INDEX}) were used to ensure the comparability. It was essential to consider the exact material hauling times for the simulation of the short-term aging process in the HMAAT. The average material hauling time of the HMA was 110 min for AF1, 70 min for AF2 and 170 min for AF3. These values were based on the inventory data from the original construction conditions. For the simulation of A_{STA} in the HMAAT three different experimental stages were performed: V_1, V_2 and V_3 and the material manipulation times in the field corresponded with the simulation times. The parameters for each conducted test in the HMAAT are shown in Table 2.

Table 2. Simulation times and corresponding start temperatures for experiments

	t = 60 min	**t = 120 min**	**t = 180 min**
T_{START}	170.5 ± 3 °C **V_1 – STA_L_60**	178.5 ± 3 °C **V_2 – STA_L_120**	187.5 ± 3 °C **V_3 – STA_L_180**

The start temperature for each experimental stage was based on the compaction temperature for the placing during construction and relevant inventory data as well as on the cooling rate of the HMA during material manipulation related to the site equipment and the weather conditions. For all tests (V_1-V_3) an average cooling rate of 0.15°C per minute was adopted. The compaction temperature ranges used during the construction of the asphalt facings correspond to today's requirements (Table 3).

Table 3. Material temperature ranges for paving and compaction in hydraulic engineering - Bitumen 70/100, (Österreichs Energie 2013)

	70/100
T_{paver}	150 - 180°C
$T_{compaction}$	≥ 120°C

3.1 Discussion and Test Results

The changes of performance characteristics (PEN_{INDEX}) due to the aging process are mean values and illustrated in Figure 10. The material properties of short-term-aged field samples showed a decrease of the PEN_{INDEX} with extended material manipulation time and the material behavior was according to expectations. AF3_STA had the strongest increase of stiffness and embrittlement, with over 43% compared to the virgin bitumen (A). AF1_TOTAL and AF3_TOTAL showed approximately the same PEN_{INDEX} (A_{TOTAL}) after 33 years in service. The comparison of AF1_STA with AF1_TOTAL displays a share of the AF1_LTA of approximately 13%. The PEN_{INDEX} after short-term aging of AF3_STA is nearly equal to the PEN_{INDEX} of AF3_TOTAL. A different distribution of the percentages in various aging stages shows AF2. The lowest share of the A_{STA} in A_{TOTAL} of the three tested facings has AF2 with approximately 40 %. This is with a high probability a consequence of the shortest material manipulation time and the connected mix temperature. Figure 4 depicts a high share of A_{STA} in A_{TOTAL}. The material investigations in (Smesnik M. 2016) as well as the performed tests for this paper confirm the high ratio of A_{STA} in A_{TOTAL} (cp. Figure 4 and Figure 10). Other investigations in (Zhengxing W. et al. 2015) have shown that the change of performance characteristics as a result of A_{LTA} depends on the depth of asphalt cover. The reason is the shortage of ROS with increasing asphalt cover depth for the chemical aging reactions (Figure 6). The aging rate decreases along with the increasing time of operation. This process also occurs when enough ROS are available. The limiting factor for the aging process (chemical reaction) is the decrease of reactants of the bitumen. The reasons for the small deviations of the PEN_{INDEX} between A_{STA} and A_{TOTAL} of AF1 and AF3 are with a high probability the strong short-term aging effects and the aging distribution over the cover depth (cp. Section 2.1 see Figure 10).

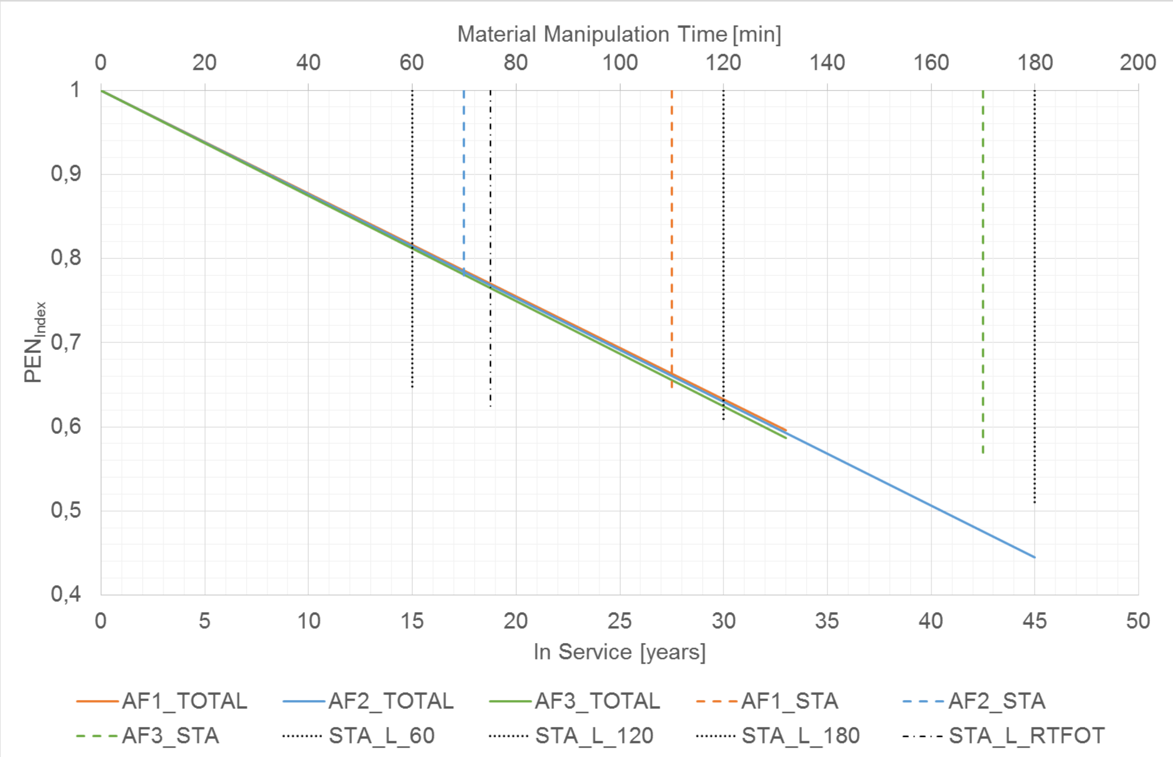


Figure 10. Comparison of field-aged with lab-aged HMA (bitumen)

3.2 Comparison of lab short-term aging methods with the aging process in the field

All performed aging experiments in the HMAAT show conservative results compared to the bitumen aging in the field (Figure 10). Especially, AF1_STA and AF3_STA display a high correlation with STA_L_120 and STA_L_180. The PEN_{INDEX} of the recovered bitumen samples of the HMAAT and the RTFOT for short material manipulation times (≤ 75 min) are too conservative. In order to avoid this problem for further simulations with short material manipulation times in the HMAAT, the amount of ROS (air volume flow through the HMA) should be lowered (≤ 300 l/min). As mentioned in section 2.2.1, the aging simulation of HMA (HMAAT) provides advantages compared to the aging of pure bitumen (RTFOT). 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.

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. OUTLOOK

In order to improve the data collective, further AFs will be analyzed. For a more detailed investigation of the aging behavior and material changes, DSR tests (CEN EN 14770 2012) will be additionally performed. The results of the current investigations as well as in (Smesnik M. 2016) indicate that correctly constructed AFs have a very high durability. Based on today's knowledge about asphalt technology and modern construction methods, it is possible to construct asphalt facings which meet the respective technical requirements and offer very good long-term behavior.

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