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Review of Lab-Accelerated Aging Techniques of Asphalt Mixes

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ABSTRACT

Bitumen aging contributes to main pavement distress due to the changes in rheological, chemical, and physical characteristics of bitumen. Mainly, aging process can be divided into two categories, the first category namely short-term aging takes place during the heating up of bitumen and aggregate, mixing, transportation, laying down, and compaction. While the second category of aging takes place during the service life of pavement which is denoted as long-term aging. Consequently, researchers' focus is to simulate bitumen aging in the lab by developing lab-accelerated methods to simulate the process of bitumen aging and studying the rate of change before and after aging. This article reviews these methods and compares the extent of the impact on lab-aged bitumen with old bitumen. The main outcome is, that the duration of exposure to high temperatures, which is the dominant method to accelerate aging process, resulted in inadequate changes in the structure of the bitumen molecule, hence, making it different from old bitumen. For that reason, using oxidants such as hydrogen peroxide showed more reliable results but requires more attention by researchers to achieve a standardized aging process of bitumen.

Keywords: Aged asphalt, Bitumen, Mixing, SARA, PAV

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مراجعة تقنيات التقادم المعجل مختبريا لخلطات الأسفلت

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الخلاصة

يساهم تقادم الزفت في مشاكل التبليط الرئيسية بسبب التغيرات في الخصائص الريولوجية والكيميائية والفيزيائية للزفت. بشكل رئيسي، يمكن تقسيم عملية التقادم إلى فئتين، الفئة الأولى وهي التقادم قصير المدى ويحدث أثناء تسخين الزفت والركام، والخلط، والنقل، والوضع، والحدل. بينما الفئة الثانية من التقادم تتم خلال العمر التشغيلي للتبليط والذي يسمى التقادم طويل الأمد. وبالتالي، ينصب تركيز الباحثين على محاكاة تقادم الزفت في المختبر من خلال تطوير أساليب معملية مسرّعة لمحاكاة عملية التقادم ودراسة معدل التغير قبل التقادم وبعده. تستعرض هذه المقالة هذه الطرق وتقارن مدى التأثير على الزفت المتقادم في المختبر مع الزفت القديم. والنتيجة الرئيسية هي أن مدة التعرض لدرجات الحرارة المرتفعة، وهي الطريقة السائدة لتسريع عملية التقادم، أدت إلى تغييرات غير متكافئة في بنية جزيء الزفت، مما يجعله يختلف عن الزفت القديم. ولهذا السبب، أظهر استخدام المواد المؤكسدة مثل بيروكسيد الهيدروجين نتائج أكثر موثوقية ولكنه يتطلب المزيد من الاهتمام من قبل الباحثين لتحقيق عملية تقادم موحدة للزفت.

الكلمات المفتاحية: التبليط المتقادم, البيتومين, الخلط, الاسفلتين, التقادم المعجل

1. INTRODUCTION

The fundamental factor in pavement degradation and deterioration that may necessitate maintenance, repair, or even the complete removal of existing roadways is thought to be bitumen aging in asphalt **(Yang et al., 2020)**. Initiation and development of bitumen aging are influenced by a number of factors, one of which is the short-term aging process of producing asphalt in the plant at high temperatures (up to 140°C), transporting it, laying it down, and compacting it **(Ismael et al., 2022)**. Long-term aging of asphalt is due to several factors such as climatic factors (air), oxidation, and mechanical and physical stresses. In order to better understand how bitumen behaves over time, studies have been conducted to model bitumen aging in the lab **(Ismael et al., 2022)**. In order to produce very durable asphalt and to permit recycling or repeated recycling, it is also important to improve material qualities and asphalt mix design **(Majeed and Sarsam, 2021)**. Considering that bitumen is a hydrocarbon molecule and that temperature changes have a significant impact on its chemical structure and bonding, new methods for modeling asphalt aging are needed. Additionally, most of the existing accelerated aging techniques using high temperatures and air for bitumen aging, which could result in variations between the final products when comparing asphalt that has been aged in a lab and asphalt that has been aged in the field, to ascertain the impact of aging on asphalt qualities, performance tests on aged mixes were conducted, and the findings were compared to those of fresh mixes **(Yang et al., 2020)**. To identify the physical, chemical, and rheological changes in bitumen qualities brought on by the aging process, bitumen extracted from aged mixtures, virgin bitumen, and lab-aged bitumen were all evaluated **(Błażejowsk and Wójcik-Wiśniewska, 2016)**.

This work aims to review previous studies interested in developing accelerated methods of asphalt aging to simulate real aging process in the field. Consequently, discuss the advantages and disadvantages of each method to suggest the most accurate method of aging.

2. BITUMEN

Bitumen has been the primary binder of contemporary roads since it was first used to pave roads in Babylon in 620 BC **(Byrne, 2005; Błażejowsk and Wójcik-Wiśniewska, 2016**). This is because bitumen can withstand subjected loads by vehicles and changes in climatic conditions. The major components of the bitumen molecule are carbon (82–88%), hydrogen (8–11%), sulfur (6%), oxygen (1.5%), and nitrogen (1%) **(Airey, 1997)**. Bitumen can be derived from industrial techniques or natural sources such as bitumen lakes **(Jung, 2006)**. The source of the mineral oil or the manufacturing method might affect the characteristics of bitumen, potentially changing its content and intricate molecular structure.

2.1. Chemical Composition of Bitumen

Researchers have devised numerous strategies to extract or analyze the chemical components of bitumen. The Corbett method **(Greaves et al., 2004; Wu, 2009; Yang et al., 2020)** by solubility of bitumen in regular heptane (non-polar solvent) is one of the most extensively used techniques. The insoluble portion of bitumen is known as asphaltene, which is the base fraction of the bitumen molecule and the most highly polar fraction. Other fractions are referred to as maltenes, which are subsequently divided into three groups in accordance with the various solvent polarities used in column chromatography **(Handle et al., 2017)**. Three fractions of maltenes with various polarities are separated after numerous cycles of adsorption-desorption. These fractions consist of resins, aromatics, and saturates. SARA stands for the four substances that make up bitumen: saturates, aromatics, resins, and asphaltene, as shown in **Fig. 1**.

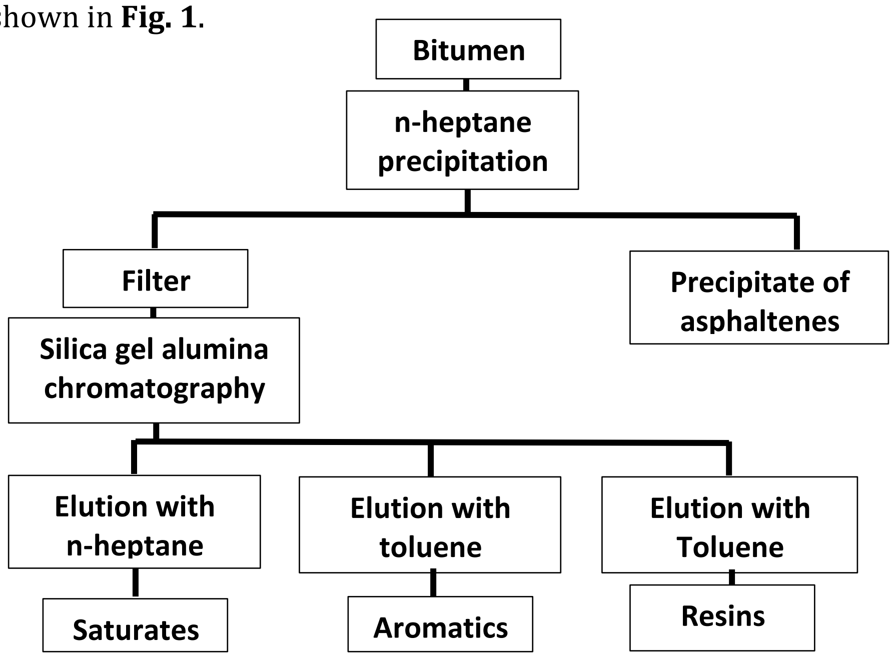

Figure 1. Corbett adsorption/desorption chromatography **(Wu, 2009).**

2.1.1. Asphaltene

Asphaltene represents the solid component of bitumen where molecules are securely linked together to create large molecules. Asphaltene comprises highly polarized aromatic rings and heteroatoms in addition to nitrogen, oxygen, and sulfur. According to **(Wu, 2009; Mullins, 2011),** this fraction constitutes 5% to 25% of the bitumen molecule. The quantity of asphaltene greatly influences the rheological properties of bitumen. During the pavement's service life, it is less sensitive and more stable at high temperatures **(Wu, 2009)**. Particle diameters vary between 5 nm and 30 nm, while molecular weights range from $1x10^3$ to $1x10^5$ g/mol **(Airey, 1997)**.

2.1.2. Saturates

Saturates are viscous, non-polar oils having molecular weights of $3x10^2$ to $2x10^3$ g/mol that are straw- or white-colored and non-polar **(Airey, 1997; Edwards and Isacsson, 2005)**. They are made up of long or short aliphatic hydrocarbon chains **(Wu, 2009)**. 5% to 20% of all bitumen is made up of saturates **(Wu, 2009)**.

2.1.3. Aromatics

When compared to saturates, aromatics have the lowest molecular weight **(Airey, 1997; Michael and Eva, 2019).** The majority of the dispersion medium for the peptized asphaltene is made up of them, which range from 40% to 65% of bitumen **(Airey, 1997)**. According to (**Wu, 2009)**, they are made of a thick dark brown liquid.

2.1.4. Resins

Resins are very polar substances that are dark brown in color, solid or semi-solid in consistency, and highly sticky **(Airey, 1997; Eva and Michael, 2018)**. According to **(Wu, 2009)**, resins are thought of as peptizers or dispersion agents for asphaltene. As a result, the amount of resins in an asphaltene mixture determines whether the bitumen is a solution (SOL) or a gelatinous substance (GEL), (**Airey, 1997**). According to (**Airey, 1997**), resins have a molecular weight range of $5x10^2$ to $5x10^4$ g/mol and a particle size range of 1nm to 5nm. These components (asphaltene, saturates, aromatics, and resins) are shown in **Fig. 2.**

Figure 2. Chemical compositions of asphalt molecule (SARA).

An indicator of colloidal instability (CI), **(Chakkoth et al., 2020; Salehfard et al., 2021),** is based on the bitumen fractions described above and is calculated as follows:

$$CI = \frac{flocculated\ constituents}{\text{dispersing constituents}} = \frac{Asphaltene+Saturates}{\text{Resins+Aromatics}} \quad (1)$$

A low CI value suggests that the asphaltenes exhibit more persistence due to being more peptized in the oil-based media. (**Airey, 1997**). Bitumen fraction structural models (SARA) are depicted in **Fig. 3.**

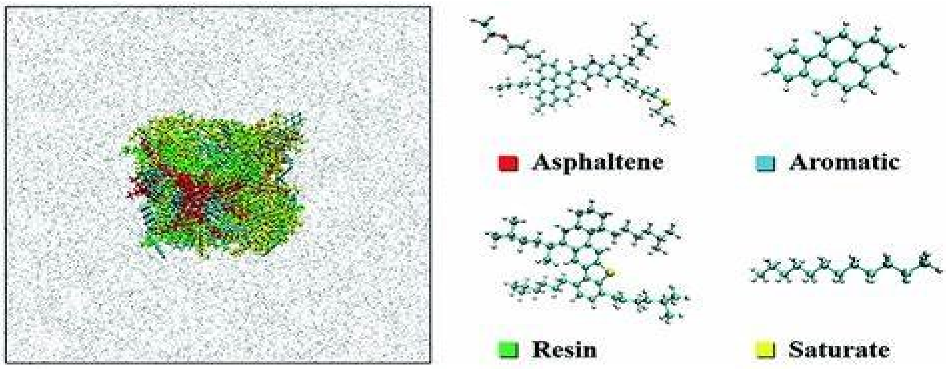

Figure 3. Structural models of asphaltene, aromatics, resins, and saturates **(Behzadfar, 2014**).

2.2. Bitumen Age Hardening

Although bitumen makes up just 5% to 7% of the total mix of asphalt, its quality greatly influences the performance of asphalt mixture by impacting the structural and functional integrity of the pavement. According to several researchers **(Petersen, 2009; Campbell and Wright, 1964; Gawel et al., 2016; Ismael et al., 2022)**, age hardening is the primary factor influencing the properties of bitumen. Bitumen, being an organic substance, is affected by various factors such as oxygen, ultraviolet light, ozone resulting from the interaction of NOx gas emissions from cars and UV radiation, oxygen levels, temperature fluctuations, and ozone. **(Wu, 2010)**. According to **(Bressi et al., 2016; Cheng et al., 2015)** external forces cause bitumen to harden, resulting in notable rheological changes such reduced penetration, higher softening point, and increased viscosity. The following is a summary of the factors that affect bitumen's age hardening:

1. Oxidation occurs when bitumen reacts with oxygen, and the rate of this reaction is influenced by temperature and binder qualities. The extent of oxidation is significantly influenced by temperature, time, and bitumen coating thickness **(Thyrion, 2000)**.
2. Volatilization is the process of lighter components in bitumen evaporating, mostly influenced by temperature **(Mousavi et al., 2023)**.
3. Polymerization involves the amalgamation of similar molecules to form larger ones, leading to an increase in hardness **(Król et al., 2017)**.
4. Thixotropy: A gradual hardening caused by a shear stress which develops over time in the bitumen; it can be partially reversed by warming up the bitumen **(Mouillet et al., 2012)**
5. Syneresis: This is the manifestation of thin, oily liquids to the outer layer of the bitumen. The bitumen hardens due to the extraction of these oily components **(Gao et al., 2021).**

6. Separation: The separation process involves the loss of oily components, resins, or asphaltenes from bitumen due to the selective absorption of certain porous particles. **(Jemere, 2010)**.

2.3. Impact of Aging on Chemical Changes of Bitumen

One of the important factors that emerges aging is the chemical changes involved where ketones are generated along with carboxylic acids, and thio-ethers as a result of oxidation of methylene and degradation of unsaturated chains and naphthenic ring structures in benzene systems during age, which then converted to sulfoxides. **(Lu and Isacsson, 2002)**. Additionally, polarity increases as a result of structural alterations, which also causes an increase in resin and asphaltene content and a decrease in aromatic content **(Abutalib et al., 2015; Wang et al., 2019; Hu et al., 2022**). In-situ tests also revealed that asphaltene content rose by 2% to 10% over an 8.5-year period **(Mills-Beale et al., 2014; Hagos, 2008)**. Additionally, environmental scanning electron microscopy (ESEM) performed on fresh and aged bitumen by Rolling Thin-Film Oven Test (RTFOT) and Pressure Aging Vessel (PAV) revealed that oxygen uptake causes asphaltene's size to rise.
The Rolling Thin Film Oven Test (RTFOT) mimics aging in the plant before its application on roads. The test is conducted in a controlled environment by subjecting thin binder films to high temperatures of 163°C. To replicate extended aging in laboratory conditions, pressure aging is utilized. PAV utilizes temperatures ranging from 90°C to 110°C and a pressure of 2.10 MPa. **(Kim et al., 1986; Zhang et al., 2011; Al-Fayyadh and Al-Mosawe, 2023**). The material undergoes significant changes when artificially aged, contrasting with its state at temperatures below 80°C, like in roads. Hence, future standardized aging testing should be conducted within a temperature range where microstructures are still present in order to derive valid conclusions regarding performance from aging trials. **(Poulikakos et al., 2016; Majeed and Sarsam, 2021)**. Changes in bitumen constitutions (SARA) over time are depicted in **Fig 4**.

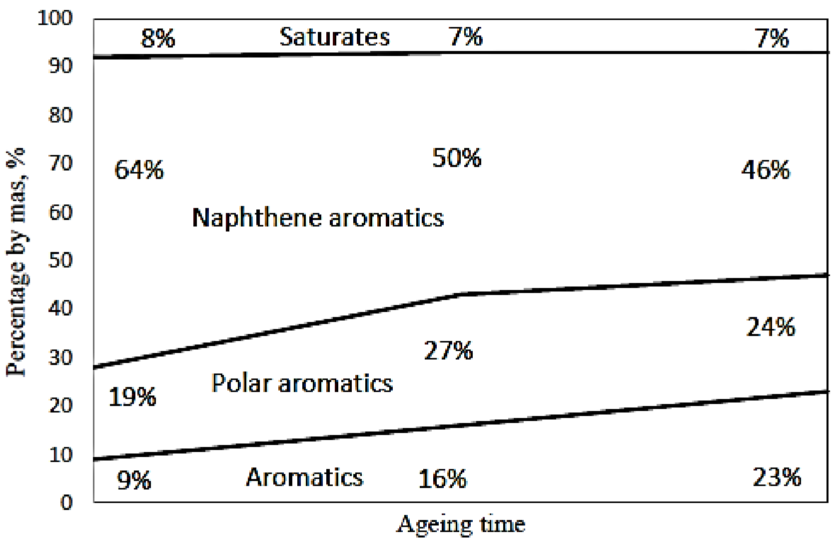

Figure 4. Bitumen undergoes fractional changes throughout time. **(Airey, 1997)**.

2.4. Determination of Aging in Bitumen

Many techniques were developed to assess the impact of aging on bitumen extracted from asphalt mixes by comparing specific properties before and after aging. These measures are sub grouped as chemical, physical, or rheological indices. Standard bitumen tests, like needle penetration and softening point (ring and ball), are conducted before and after aging. After that, the physical or empirical aging index is calculated as a proportion of aged to unaged bitumen or the difference in softening point. On the other hand, aging increases the complex modulus and decreases the phase angle, which can be measured by examining how these rheological parameters of bitumen change when changing loading patterns and temperatures **(AASHTO T315-10, 2010; Yu et al., 2013; Dhuha and Hasan, 2021)**. Chemical indices such as colloidal instability (CI) can be used to determine bitumen aging. High confidence interval values indicate accelerated aging of bitumen. **(Subramanian et al., 1996; Paliukaite et al., 2014)**. The infrared spectrum's area and peak height at wavenumbers 1030/cm (S=O) and 1700/cm (C=O) are utilized to measure the chemical alterations resulting from aging in Fourier transform infrared spectroscopy (FTIR), which is an alternative technique **(Lucena et al., 2004)**. **Fig. 5** illustrates how both short-term and long-term aging affect the viscosity ratio (age index) of pavement over time. **(Read and Whiteoak, 2003)**. The primary factor influencing the bitumen's aging index is the manufacturing of asphalt.

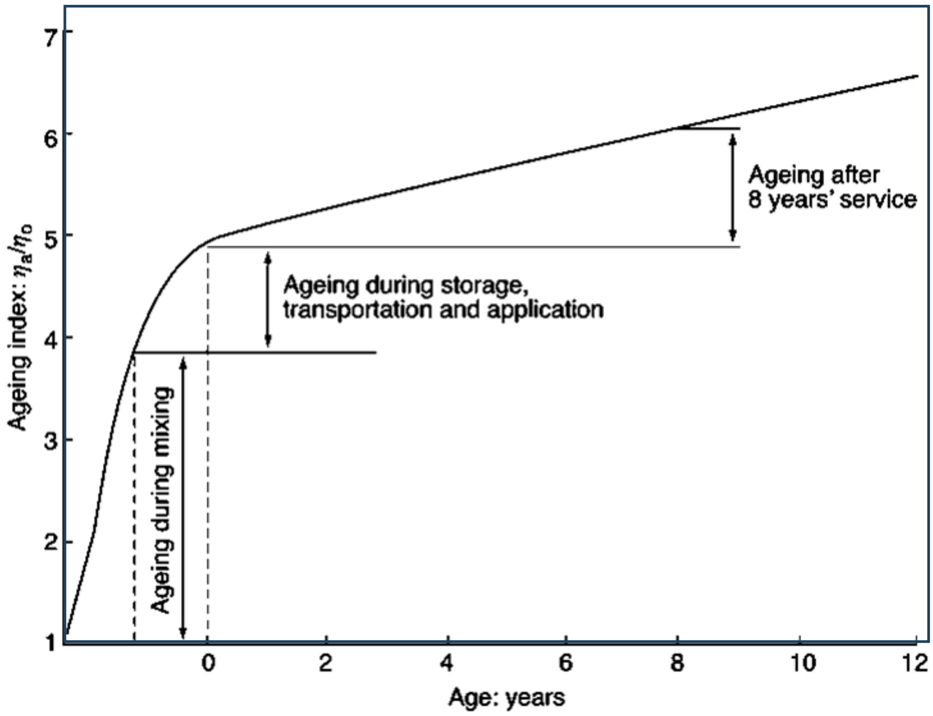

Figure 5. Aging index during service life, in years **(Read and Whiteoak, 2003)**.

2.5. Oxygen Diffusion into Bitumen

The bitumen age hardening process is mostly caused by oxygen **(Dickinson et al., 1958; Das et al., 2014; Rad, 2018)**. It was believed that just the top 40mm of the asphalt pavement could permit air penetration **(Han, 2011)**. Likewise, air channels inside asphalt mixtures was found to be initiated due to the connected air voids and these channels are running from top to bottom. Such results were detected through the utilization of computed tomography (CT) as well as image-analysis techniques **(Han, 2011)**. Oxygen pressure may affect the hardening process of asphalt. Oxidation kinetics response in addition to the diffusion of oxygen through layers of particles in a maltene environment are techniques used to determine this effect. As temperature and/or oxygen pressure rise, bitumen hardening rises **(Glover et al., 2002)**.

2.6. Laboratory Aging Techniques of Bitumen

Numerous protocols were introduced to simulate aging of bitumen in the plant and in service, and they can be listed into the following:

1. The Thin Film Oven Test (TFOT) (ASTM D 1754)
This test is a common test for determining how temperature and oxidation together affect asphalt binder. A pan is filled with a thin layer of bitumen, and it is kept at 163°C for five hours in a convection oven. According to the change in mass (given as a percentage) and/or the bituminous binder's properties, such as penetration (ASTM D5-6, EN1426), softening point (ASTM D36, EN1427), or dynamic viscosity (ASTM D2171, EN12596), before and after the oven, the effect of hardening is determined.

2. The Rolling Thin Film Oven Test (RTFOT; ASTM D 2872)
In order to simulate aging in a hot-mix asphalt plant, the SHRP binder specification uses the Rolling Thin Oven Test (**Fig. 6**) as a standard test. For the RTFOT aging test, 50 g of bitumen is put into eight separate, cylinder-shaped bottles with an aperture at one end. The bottles are placed in a 163°C oven for 75 minutes, or 85 minutes with an air flow at a rate of 4lit/min according to SHRP requirements. The bottles are placed on a carousel and occasionally filled with brand-new hot air. The hardening effect is established as in the TFOT. According to studies, the RTFOT often volatilizes more binder components since it is roughly 10% more severe than the TFOT **(Zupanick and Baselice, 1997)**. The RTFOT test subjects a new outer layer of bitumen, which leading to minimize skin growth compared to the TFOT test.

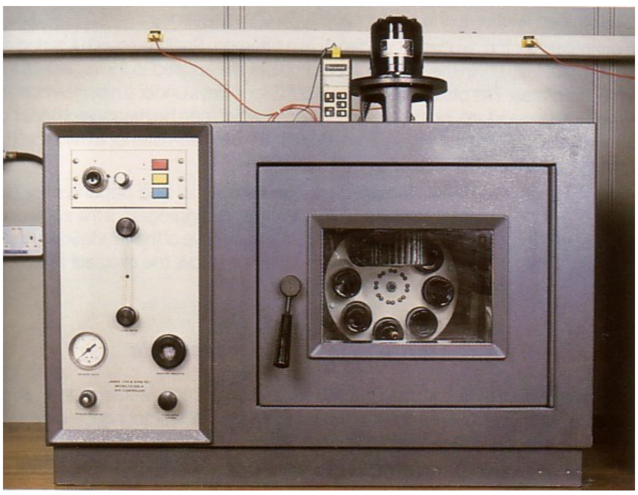

Figure 6. RTFOT aging apparatus **(Hagos, 2008)**.

3. The German Rotating Flask Test (GRFT; DIN 52016)
Instead of the previously mentioned methods of aging, the German Rotating Flask Test was created in Germany (**Ramaiah et al., 2004**). In the GRFT, 100g of bitumen (or 200g in the case of the modified GRFT) is put in a spherical flask. As seen in **Fig. 7**, this flask is inverted and submerged in an oil bath that is heated to 165°C. The test duration is 150 minutes, equivalent to 210 minutes in MGRFT. 500 cubic centimeters per minute (2000 milliliters per minute in the Modified Granular Rate Filtration Test) of air is flowing through the flask at a rate of 20 revolutions per minute. The testing vessel is closed, hence the type and flow of used gas in the experiment is kept under controlled conditions. During the test, the sample is flipped over continuously due to the rotated vessel. At the same time, aging process proceeds with preventing skin formation as well as keeping the binder layer in place. To eliminate shortcomings of radiant heating in traditional ovens, an oil bath was used in this test to enable quick heating of bitumen. The testing device can be changed to enable the collection of components that have evaporated. A limitation of this test is the creation of volatiles where it was found that it creates less volatiles (1/3) when compared with other aging techniques such as the RTFOT or TFOT leading to less aging potential.

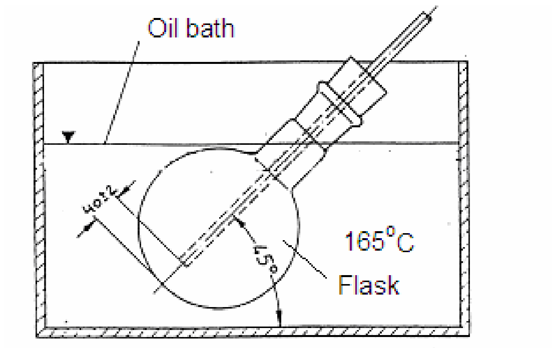

Figure 7. Setting up the German Rotating Flask Test (GRFT) **(Hagos, 2008)**.

4. The Pressure Aging Vessel (PAV, SHRP test method B-005, EN 14769)
Asphalt binders are subjected to aging in the field during service life due to several factors such as environmental circumstances and other factors after short-term aging under the conditions of the road placement. The development of bituminous mixes' long-term behavior and performance characteristics is greatly influenced by this third-aging stage process **(Francken et al. 1997; Goosen and Jenkins, 2023)**. An asphalt mixture in service oxidizes with time, which is the main cause of long-term aging. The occurrence of this type of aging is a result of gradual oxidation process that occurs when the binder comes into contact with the environment or air. PAV is a SHRP aging technique designed to mimic the oxidation process that occurs over the course of a pavement's service life. Using the RTFOT (SHRP standard test) approach, the binder is first aged for the short term. During a standard PAV test (**Fig. 8**), 50g of binder is put into a prepared pan with a diameter of 140 mm (the thickness of the binder film will be about 3.2 mm), which is then set in a shelf rack that can hold up to 10 pans. During the 20-hour-long aging process, the aging vessel's temperature is kept at either 85 °C (PAV 85), 90 °C (PAV 90), 100 °C (PAV 100), or 110 °C (PAV 110), and its pressure is kept at 2.1 MPa. Chemical changes similar to those caused by field aging can be achieved by aging at temperatures below 100 °C. Another long-term testing technique is the HiPAT (High Pressure Aging Test), which utilizes PAV equipment at a low testing

temperature as well as longer time. The 65-hour HiPAT aging test is carried out at 85 °C and 2.1 MPa air pressure.

Figure 8. PAV test equipment with a rack **(Hagos, 2008)**.

A change in the binder qualities that differ from reality may arise from accelerated aging experiments that are undertaken at increased temperatures above the temperatures of the actual pavement, according to researchers. Researchers often critique the PAV aging method for being a static test with uneven oxygen diffusion, leading to differences in aging rates between the sample's surface and interior **(Verhasselt, 2004).** Polymer migration during PAV aging of PMB materials has been observed by examining the top and bottom of the aged specimens.

5. The Rotating Cylinder Aging Test (RCAT)

In order to model the aging process of binders in the plant and service, the Belgian Road Research Center (BRRC) developed the Rotating Cylinder Aging Test (RCAT), shown in **Fig. 9 (Glover, 2007; Czajkowski et al., 2023)**. Because the cylinder is rotating, aging process is consistent, and due to the sufficient size of the cylinder, enough quantities of aged bitumen can be obtained for testing. One drawback of this test is the testing time which is regarded long in comparison with other tests. However, long testing time can be employed by taking samples of bitumen at different time points to study and track any changes in bitumen's properties while the testing process is ongoing. Additionally, simulating aging process in the plant and in service in one sample of bitumen is considered another significant benefit of the RCAT test that minimizes intermediate sample handling procedures.

The RCAT aging procedure is as follows:

a. stainless-steel cylinder is filled with 500 to 550 g of binder.

b. rotation of cylinder is set to a rate of 1 rpm when simulating long-term aging of bitumen

c. A grooved stainless-steel roller to push and spread a 3 mm film thickness of binder inside the cylinder so as to homogenize the bitumen sample and also to subject new layer of bitumen consistently.

d. The cylinder's atmosphere is refreshed by a consistent oxygen supply of 4.5 liters per hour. While a temperature of 90°C may expedite the testing period, the recommended operating temperature is 85°C. The test duration is 240 hours at 85°C or 144 hours at 90°C.

Although a temperature of 90°C may be preferable to shorten the testing period, 85°C is the suggested operating temperature **(Hagos, 2008)**.
When utilizing the RCAT to simulate short-term aging, the cylinder is set at 5 rpm (instead of 15 rpm in the RTFOT method), an air input rate of 4 liters/min, and the test is conducted for 235 5 min (4 hours) at a temperature of 163°C for an equivalent degree of aging as in the RTFOT (**Verhasselt 2004; Kerim, 2022**).

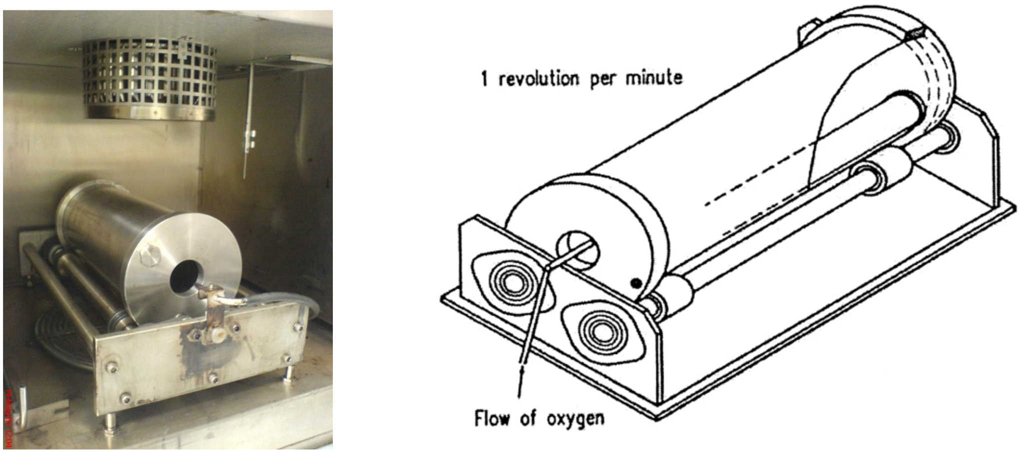

Figure 9. RCAT instrument used for accelerated aging of bituminous binders **(Hagos, 2008)**

3. AGING OF ASPHALT

As previously stated, aging of bitumen is directly affecting the overall performance of asphaltic mix. Various approaches were developed to mimic the process of age hardening of asphalt. The simulation process is important to conclude how it will behave in the future or extend the durability of pavements. These tactics involve subjecting materials to air at high temperatures for different durations to simulate the various stages such as mixing, transporting, putting down, and compaction. It is essential to replicate the extended deterioration of pavement in real-world conditions, caused by temperature fluctuations, mechanical stress, and other factors. Asphalt aging can be categorized in two main categories:
- Short-term aging **(Sujit, 2023)**: According to some standards (SHRP) to simulate this process of aging un-compacted mixtures are heated for four hours at 135°C before compaction, with stirring and turning every hour. This process reflects the process of aging in service of two years or less, as found in SHRP B-003.
- Long-term aging: (**Burak et al, 2023**)

In contrast to the previous method, the mixture in this method is compacted and kept at 85°C in an oven for a period of 120 hours to simulate this process of asphalt aging (SHRP B-003). Moreover, some laboratory methods were also developed to introduce new methods of aging **(Van Den Berg, 2011)**.
A lab-based accelerated aging procedure using a tri-axial chamber is proposed as an alternative to applying high temperatures to age asphalt. This procedure comprises the employment of an oxidant agent in the form of forced gas through the specimen (**Fig. 10**). Ozone and nitric oxides are included in the oxidizing agent to accelerate the oxidation process. Aging time can be extended up to four days and at any desired temperature such as (60 °C) to simulate real aging temperature with a flow rate of 1 l/min. The effectiveness of

this procedure was demonstrated by dynamic tests of asphalt such as modulus of stiffness of unaged sample compared to lab-aged specimens. Additionally, bitumen dynamic test such as Dynamic Shear Rheometer of the recovered binder from aged specimens was also used in the evaluation of this procedure **(Steiner et al., 2014)**.

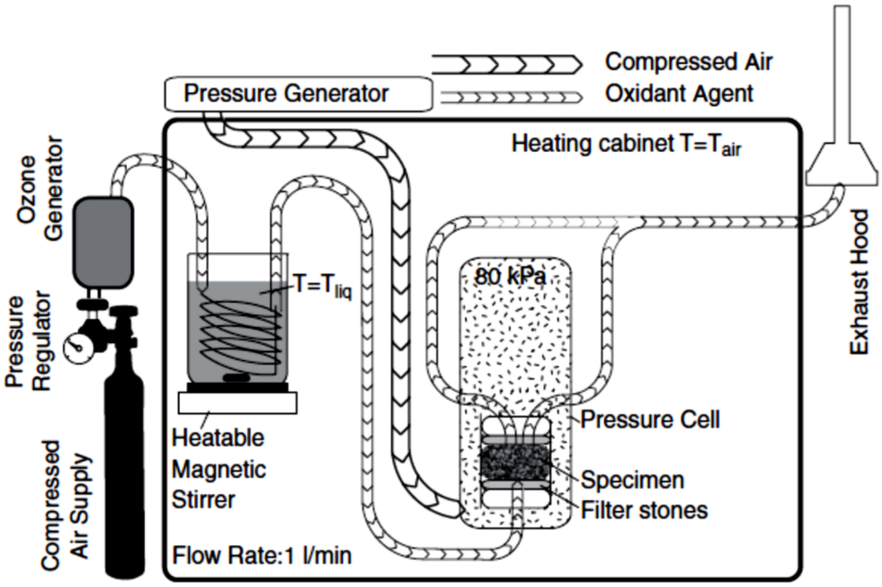

Figure 10. Apparatus asphalt aging **(Steiner et al., 2014)**.

Recently, some researchers established an aging method where the specimens were heated to 85 °C for 66 hours and then placed in cold water at 20 °C for 6 hours. This was followed by two cycles of heating to 85 °C for 42 hours and cold water for 6 hours in the first cycle. In the second cycle, the temperature is kept identical while the duration is extended to 66 hours of heating **(Raab et al., 2017; Meng et al., 2021**). Following that, performance tests were conducted in accordance with German requirements for fatigue, and rutting resistances as well as rigidity modulus. Moreover, it was concluded that the modulus of stiffness and fatigue resistance were higher in aged asphalt compared to unaged asphalt. However, resistance to rutting in unaged asphalt was lower compared to aged asphalt **(Yousif et al., 2015; Guo et al., 2016)**.

4. CONCLUSIONS

Aging of asphalt is a continuous process that initiates from the mixing of bitumen with aggregate in the production plant and service. According to the studies reviewed and methods of aging used to simulate asphalt aging in the lab, it can be concluded that using high temperatures in the lab to accelerate aging process is the predominant method. However, some researchers tried to reduce these temperatures to overcome the issue of conformational changes in bitumen due to high temperatures. Additionally, some conclusions can be summarized below:

1) Bitumen composition is highly affected by higher temperatures, especially during mixing with aggregate. This characteristic is obvious due to the prevalence of light hydrocarbon molecules.
2) At higher temperatures (60 °C to 140 °C) bitumen exhibits compositional and morphological changes that produce hard and sensitive bitumen to crack during the service life of pavement.

3) The existing approaches of hastening the aging of asphalt generally include raising the temperature of the storage or mixing of the asphalt mix. Asphalt is produced at high temperatures, therefore these methods could simulate the short-term aging process during mixing and shipping. However, because bitumen's behavior is greatly influenced by temperature, long-term aging cannot be mimicked at high temperatures.
4) The use of oxidizing species such as O_2 or O_3 provides a promising approach towards accelerating bitumen aging at comparative temperatures to that in real situations.
5) Short-term aging speeds up the aging process of bitumen, making asphalt more prone to cracking. Therefore, reducing the temperature of asphalt heating-up and mixing is important compared to that of current methods of mixing to minimize the aging process.
6) Among aging methods in the laboratory, the method implemented by Rolling Thin Film Oven Test (RTFOT) seems a dependable method to simulate aging process in the asphalt plant, and explain the rheological changes in bitumen.
7) The aging process in the service of asphalt can be simulated by a Pressure aging vessel (PAV) but for a limited period of pavement life (around 10 years) while, for extended life, it is important to develop such a technique that can simulate the aging process on the long-term.

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Credit Authorship Contribution Statement

Haydar: Writing – original draft, Validation, Methodology.
Nabeel and Dmytro: Review & editing, Validation, Proofreading.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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