

1 Review

2 **Bitumen aging – a serious technological and environmental is-**
3 **sue: A review of laboratory evaluation and prediction methods**4 **Paweł Czajkowski**^{1,2}, **Andrzej Przyjazny**³ and **Grzegorz Boczkaj**^{1,4,*}5 ¹ Department of Sanitary Engineering, Faculty of Civil and Environmental Engineering, Gdańsk University of
6 Technology, Poland; E-mail: grzegorz.boczkaj@pg.edu.pl7 ² Rafineria Gdańska, Elbląska 135 Str, 80-718 Gdańsk, Poland; Email: pawel.czajkowski@rafineriagdanska.pl8 ³ Department of Natural Sciences, Kettering University, 1700 University Avenue, Flint, MI 48504, USA; E-mail:
9 przyjaz@kettering.edu10 ⁴ EkoTech Center, Gdansk University of Technology, G. Narutowicza St. 11/12, 80-233 Gdansk, Poland11
12 * Corresponding author: Dr Grzegorz Boczkaj, Assoc. Prof., PhD. Sc. Eng. Gdansk University of Technology,
13 Faculty of Civil and Environmental Engineering, Department of Sanitary Engineering, 80 – 233 Gdansk, G.
14 Narutowicza St. 11/12, Poland. Fax: (+48 58) 347-26-94; Tel: (+48) 697970303; E-mail: grze-
15 gorz.boczkaj@pg.edu.pl16 **Abstract:** Changes in the properties of bitumen binders that occur as a result of aging have a huge
17 impact on the durability of products made of them. In particular, asphalt pavements, which con-
18 stitute the most common use of petroleum bitumen, are susceptible to damage resulting from the
19 increasing stiffness of the bitumen during its life cycle. Increased stiffness of asphalt pavements
20 reduces the pavement resistance to low-temperature cracks and fatigue cracks, ultimately leading
21 to the loss of their functional properties and the need for road repair. The rate of changes in bitu-
22 men properties is influenced by many factors, the most important of which are environmental
23 conditions, technological parameters of binder processing, and physicochemical properties. The
24 greatest impact on minimizing the adverse effect of aging is the use of asphalt suitably resistant to
25 aging and changing the technological parameters of its application. This article reviews the litera-
26 ture on the key bitumen aging laboratory procedures that are used to assess bitumens for their
27 suitability for use in road construction. The short-term (RTFOT test) and long-term (RTFOT tests
28 followed by PAV test) methods are most commonly used in the world to simulate bitumen aging.
29 The review also presents the most important steps of aging procedures, their advantages and
30 limitations as identified by the authors of this publication, and a review of new laboratory tests that
31 are proposed as more effective and reliable methods of aging.32 **Citation:** To be added by editorial
33 staff during production.34 Academic Editor: Firstname Last-
35 name

36 Received: date

37 Accepted: date

38 Published: date

39 **Publisher's Note:** MDPI stays
40 neutral with regard to jurisdictional
41 claims in published maps and
42 institutional affiliations.43 **Copyright:** © 2022 by the authors
44 Submitted for possible open access
45 publication under the terms and
46 conditions of the Creative Commons
47 Attribution (CC BY) license
48 (<https://creativecommons.org/licenses/by/4.0/>).32 **Keywords:** Bitumen; Asphalt binder; Laboratory aging methods; Roads; Chemical degradation;
33 Oxidation.34 **1. Introduction**35 Petroleum bitumen is a well-known product for the construction of asphalt pave-
36 ments. In Poland, at the end of 2019, over 80% of the roads in the highest traffic category
37 were made with asphalt binder [1, 2]. On the other hand, in Europe, this share amounts
38 to about 90%, although it is difficult to verify because relevant statistics are not available.
39 In the United States, according to the analysis based on 2014 data, there are about 94% of
40 roads with asphalt surfaces [3]. Currently, both in Poland and throughout Europe, a wide
41 range of bitumens for road construction is available, ranging from traditional petroleum
42 bitumens produced during the processing of crude oil through polymer modified bitu-
43 mens, and ending with special bitumens containing additives improving the functional
44 properties of the product. Depending on the end use of a given road, the correct selec-
45 tion of bitumen and asphalt for the pavement structure largely determines its durability.

47 The properties of bitumen are variable in its life cycle. Bitumen is susceptible to ag-
48 ing, which depends on the type of crude oil it comes from, through the production
49 technology to the technology of application of the final product. In addition, asphalt ag-
50 ing continues over the entire life cycle of the end product. In simple terms, this process
51 changes the chemical composition of the binder and, consequently, the physicochemical
52 parameters, resulting in an increased hardness of asphalt, resistance to flow as well as
53 brittleness. Considering the durability of the road surface, the changes that occur during
54 the aging process are unfavorable. Although it would seem that the hardness of the
55 binder, which increases with time, allows for increased resistance to road rutting, in the
56 overall balance, changes in asphalt adversely affect the life of the pavement, causing its
57 significant reduction. The changes taking place in the asphalt during the use of the road
58 contribute to the deterioration of low-temperature properties and the reduction of the
59 fatigue resistance of the asphalt pavement, which determine the durability and suitability
60 of the pavement for carrying traffic loads.

61 The phenomenon of changes in the properties of asphalt was described, among
62 others, in the work from the 1960s [4], where it was proved that the changes occur most
63 intensively in the outer layer of the road, the so-called wearing course. Bituminous
64 binder parameters currently characterized by a dynamic shear rheometer (DSR) include
65 the complex shear modulus (G^*) and the phase angle (δ). With the aging of the asphalt
66 pavement, higher G^* and lower δ are recorded in the binders recovered from the upper
67 layers compared to the bitumens used in the binder and subbase layers [5]. The binder
68 undergoes chemical and physical changes under the influence of cycles of temperature
69 changes, contact with moisture, air, especially oxygen, and civilization pollution occur-
70 ring in it, as well as UV radiation and transferred loads. The deeper layers of the surface,
71 *i.e.* the binder layer and subbase, have limited contact with factors accelerating the aging
72 process compared to the wearing course.

73 When the road requires renovation, the available road technologies make it possible
74 to recover the previously used construction material from the pavement, which is called
75 reclaimed asphalt. It consists of aggregate surrounded by asphalt mastic, *i.e.* a binder
76 with a mineral filler. During the renovation, after several dozen years of pavement
77 use, with increasing inflation, the material used often has a value many times higher than
78 during road construction. Therefore, one of the aspects driving the development of recy-
79 cling is financial benefits. In addition to the aspects resulting from technical or business
80 requirements, the use of sustainable development strategies, especially limiting the im-
81 pact on the natural environment, is becoming more and more popular in organizations.
82 Therefore, the future of solutions based on the reuse of recovered asphalt for the con-
83 struction of new roads looks bright.

84 2. Chemical structure of bitumen and effects of hardening of binder on the chemical 85 composition

86 The chemical structure of petroleum asphalt is determined by the properties of
87 crude oil and the production technology used to achieve the final parameters of the bi-
88 tuminous binder. Bitumen is usually one of the highest boiling, high viscosity fractions
89 obtained in the process of refining crude oil. Only the residues after extraction with
90 propane or butane of vacuum fractions and petroleum coke are characterized by a higher
91 concentration of compounds with the highest (relative to crude oil components) boiling
92 point and the largest number of carbon atoms.

93 Detailed chemical analysis of asphalt is practically impossible to perform, mainly
94 because of the complex structure of chemical compounds and the number of isomers
95 present in the asphalt and their variability, depending on the variability of the crude oil
96 composition. Therefore, in the oil and construction industry, there is no bitumen speci-
97 fication based on a chemical analysis of its composition, and there are no known correla-
98 tions between the chemical properties of bitumen binders and the performance parame-

ters of bitumen, which can be used universally, *i.e.* regardless of the origin of crude oil and bitumen production technology. Application of methods of instrumental analysis such as visible light (VIS) and near ultraviolet (UV) spectroscopy, Fourier transform infrared spectroscopy (FT-IR), nuclear magnetic resonance spectroscopy (NMR) combined with mass spectrometry (MS), allows to obtain still incomplete knowledge about the chemical structure of asphalt binders [6]. Nevertheless, the analysis of the composition enables the explanation of changes in properties that occur, for example, with aging. In addition, chemical analysis allows for the identification of changes caused by chemical modification of bitumen, the assessment of the effectiveness of such modification, or the durability of the modification effects during the life cycle of the asphalt pavement (durability and stability of bitumen modification). However, it should be borne in mind that in most cases the identified chemical changes are not consistent with changes in the rheological properties of bitumen [7].

Due to the complexity of its structure, in order to determine the approximate chemical structure of bitumen, both elemental analysis (C, H, N, S, O) and the group composition analysis, the so-called SARA (the name comes from the first letters of four hydrocarbon groups, *i.e.* *Saturates Aromatics, Resins, Asphaltenes*) are still used today. The group composition test divides the binder sample into hydrocarbon compounds that differ in polarity, *i.e.* from the least polar saturates, through aromatics, resins and asphaltenes.

Elemental analysis is an analytical technique that is used in a wide range of applications and industries. The most commonly used technique for analyzing the elemental composition CHNSO is the procedure involving the combustion of a sample and then analyzing the gaseous combustion products (CO_2 , CO, H_2O , NO_x , SO_2 , etc.). The combustion products are determined by gas chromatography, with which the percentages of C, H, N, and S can be determined. The oxygen content is determined in the second stage of determination by pyrolysis. The diagram of the determination of the elemental composition (C, H, N, S, O) of asphalt is illustrated in Figure 1.

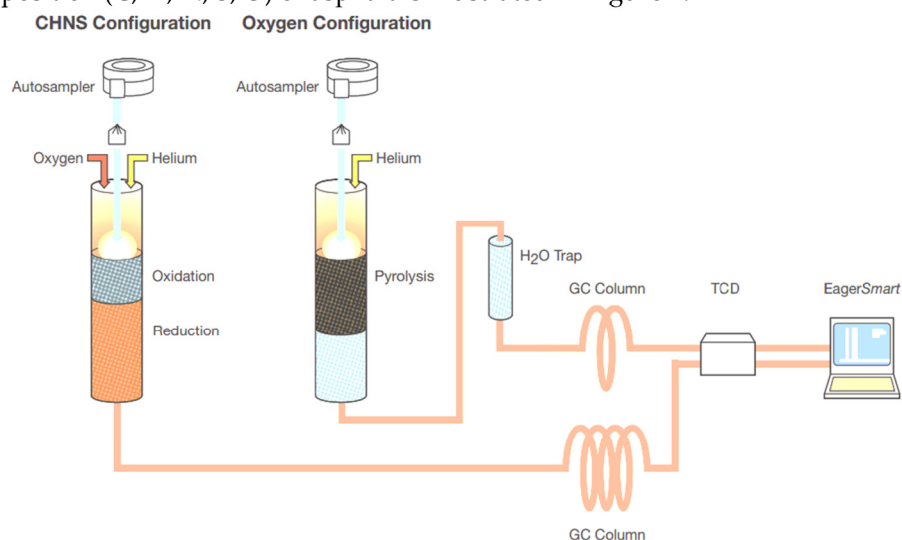


Figure 1. CHNS/O configuration [8].

The separation of asphalt into group components is most often carried out by following ASTM-D4124 [9]. The method involves the separation into four defined fractions of petroleum hydrocarbons, *i.e.* saturated, naphthenic-aromatic, polar aromatic (resins), and insoluble in *n*-heptane (or isoctane) asphaltenes. The standardized method was developed and is evolving based on the analytical procedure used by Corbett-Swerbrick [10]. The principle of dividing into individual groups is shown in Figure 2.

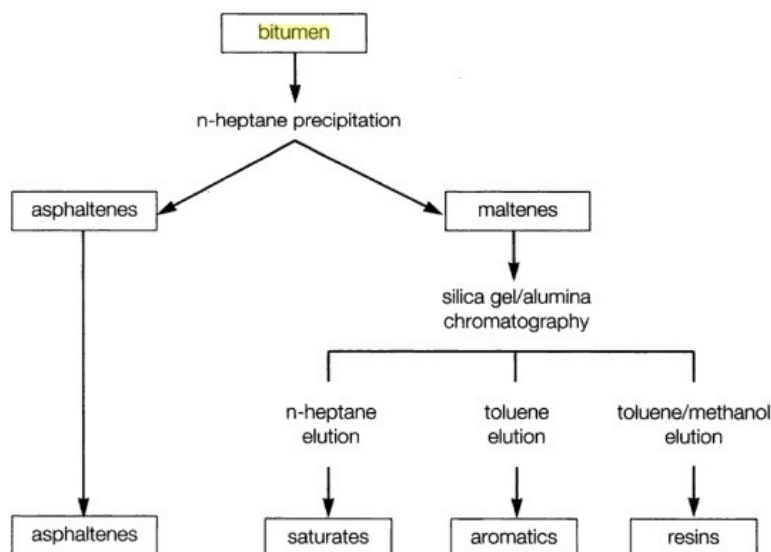


Figure 2. Schematic for the group separation of chemical constituents in bitumen.

In terms of its chemical composition, the bituminous binder produced by the processing of crude oil is a mixture of high-boiling hydrocarbons, most of which have a boiling point above 525 °C. The elemental composition by weight of the binder used in road construction is usually 80-88 % carbon, 8-12 % hydrogen, 0-9 % sulfur, 0-2 % nitrogen, and 0-2 % oxygen. The remaining elements, such as vanadium, nickel, and magnesium, are within a maximum range of several hundred ppm [11]. In terms of its chemical structure, the binder is described in the literature using colloidal or micellar models and recently using the so-called microstructural model. As part of the SHRP program, which is described in more detail in the sections on aging and bitumen specification, a chemical model of bitumen was also developed which, according to the authors, better explains the viscoelastic behavior of the binder than, for example, the micellar model. In the micellar model, the molecules with the highest molar mass – asphaltenes, form agglomerates that are dispersed in a matrix of maltenes consisting of resins, aromatic and saturated hydrocarbons. The microstructural model assumes that bitumen is a monophasic mixture of very complex hydrocarbons of polar (asphaltenes and resins) and nonpolar (aromatic and saturated hydrocarbons). In this system, there are no micelles, networks, or “floating” islands of asphaltenes. However, the fact is that a mixture of fractions with different polarities and molar mass interact with each other to form chemical complexes. Between nonpolar compounds, polar substances form these complexes as a result of weak electrostatic attractions, hydrogen bonds, and, to a lesser extent, through $\pi - \pi$ bonds of aromatic hydrocarbon rings or van der Waals forces in the case of long-chain hydrocarbons [12]. Intermolecular bonds can be broken by temperature increase or shear forces; thus, the bitumen binder after the destruction of these assemblies, *e.g.* as a result of increasing the temperature, behaves like a Newtonian liquid, and when it is supercooled, the bonds re-form, but in a slightly different configuration. An illustration of the microstructural model is presented in Figure 3.

137
138
139
140
141
142
143
144
145
146
147
148
149
150
151
152
153
154
155
156
157
158
159
160
161
162
163
164

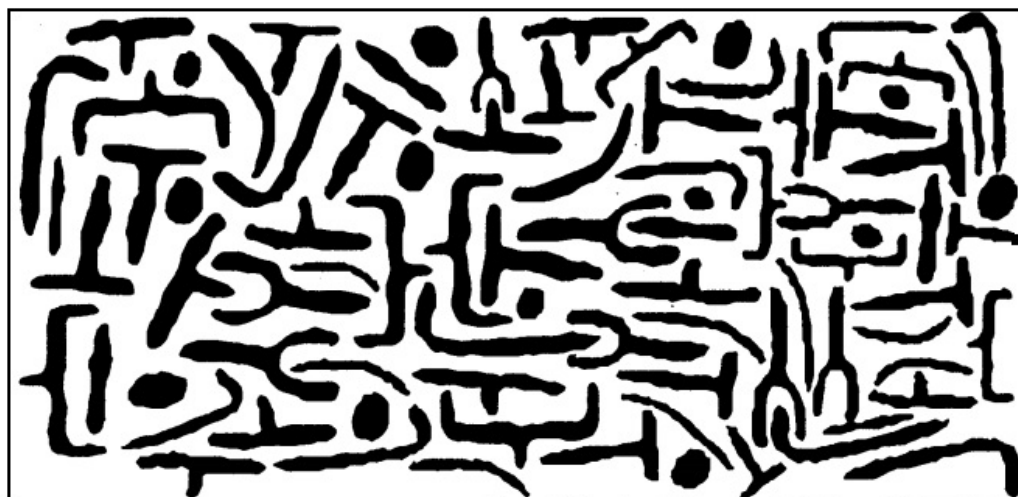


Figure 3. Model of the chemical structure of bitumen developed in the SHRP program [13]. The polar hydrocarbon systems are shown in black, while the white fields are the area representing nonpolar hydrocarbons.

Bitumen with the desired properties and chemical composition is a material characterized by the appropriate proportion of polar and nonpolar fractions. The share is difficult to define unequivocally as it depends on the source of origin and the technology of production of the bituminous binder. However, this specific balance in the chemical composition is a balance of substances that ensures the desired resistance of the material to damage. The low-temperature stability is determined mainly by the composition of the nonpolar fraction, while the fatigue cracking resistance and high-temperature deformation resistance depend on the share of polar fractions. The higher the share of polar fractions, the higher the properties of asphalt at a higher temperature, while the resistance to damage at intermediate temperatures decreases.

Aging should be defined as a change in the properties of the asphalt binder as a result of chemical and physical changes that take place under the influence of environmental conditions such as oxygen, temperature, moisture, civilization pollution present in the air, and radiation (especially in the UV range). When used in road construction, there is an additional impact of vehicle traffic and the influence of components used for the production of asphalt mix. The oxidations by oxygen as well as evaporation and adsorption of fractions in the mineral components of asphalt mix, taking place at high processing temperatures, have the greatest impact on the rate and scope of changes in asphalt. The most intensive changes registered during the life cycle used in road construction (Figure 4) are related to the asphalt mix production process [14]. The subsequent stages associated with transport and asphalt mix incorporation are of lesser importance, and due to the decreasing asphalt mix temperature compared to the previous stages, the aging process of the binder strongly slows down at the stage of usage of the asphalt pavement. On the other hand, the use of an asphalt road is designed for at least 30 years, and more often for about 50 years, so due to the duration of the road's operation, the long-term aging stage also plays a significant role in the durability of roads.



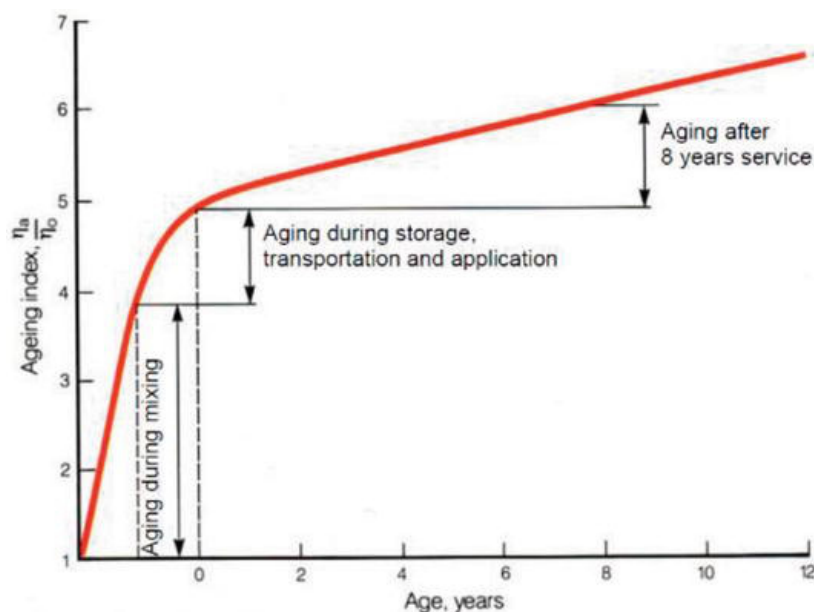


Figure 4. Aging effects on binder properties represented by the viscosity ratio index during the life of the bitumen [14].

On the basis of infrared spectroscopy (FTIR), it is possible to estimate the changes that occur in bitumen binder, using the identification of asphalt functional groups that undergo oxidation during the life cycle. With the IR spectra of the asphalt before and after aging and using the relationship between the peak area of the group undergoing chemical changes as a result of aging to the peak area, *e.g.* of aliphatic groups ($-\text{CH}_2\text{CH}_3$ or $-\text{CH}_3$), appropriate aging indices can be determined. An example of the FT-IR spectrum after aging is presented in Figure 5, while the relationship for the calculation of C=O Index is given by the following formula (1):

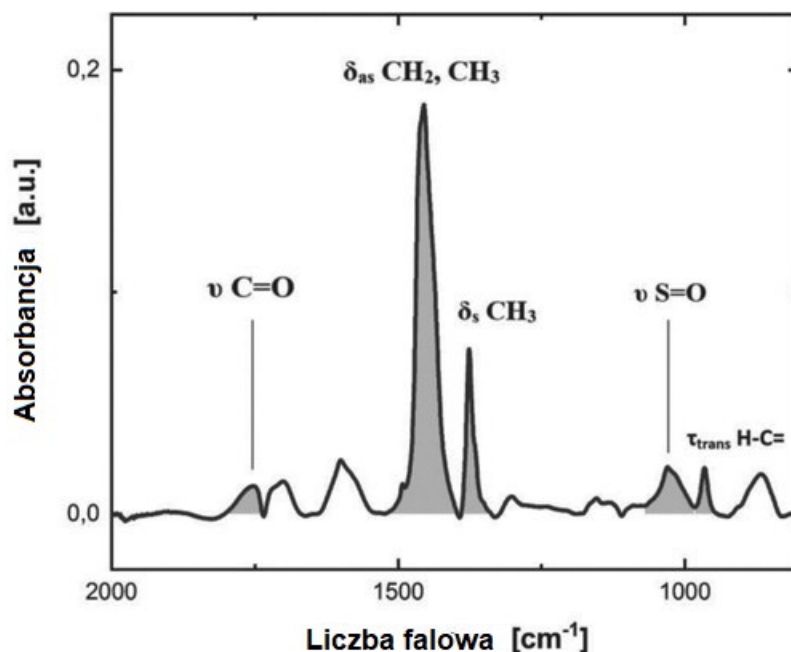
$$\text{ICO} = A_x/A_y, \quad (1)$$

where:

A_x – peak area at wavenumber $1666\text{--}1746\text{ cm}^{-1}$, characteristic for vibrations of the $-\text{C}=\text{O}$ bond,

A_y is the reference peak area of the aliphatic group at $1319\text{--}1520\text{ cm}^{-1}$.

The studies based on the recorded CO and SO indices showed [15] that the identified changes in the chemical composition of the bitumen after short-term aging are insignificant, while only after long-term aging changes indicating a greater intensity of oxidation are detected. However, *e.g.* in modified bitumens, polymer degradation is detected, which is indicated by the SBS index, an aging index suitable for the modifier of the SBS type (styrene-butadiene-styrene block polymer).



Absorbancja = Absorbance. Liczba falowa = Wavenumber

Figure 5. An example of an FT-IR spectrum [15].

On the other hand, based on the results of determination of the SARA group composition presented *e.g.* in [16], it can be concluded that in the aged asphalt (designated as OA) the content of aromatic compounds is reduced compared to the proportion of this fraction in unaged bitumen (designated as VA), while the content of resins and asphaltenes increases, respectively. The above changes are a result of the evaporation of light components and the conversion of other hydrocarbons into more complex ones with a higher molar mass. Figure 6 presents the selected research results of the authors of the above work. It should be noted that in the mixtures tested in this paper, unaged and aged bitumen, where selected rejuvenating agents (substances regenerating the properties of the product) were additionally used, it has been shown that it is possible to achieve similar shares of individual groups of hydrocarbons, which were characteristic of asphalt before aging. Samples of mixtures were marked as N1 - N5 and C1 - C5, where N and C denote the type of rejuvenating agent used.

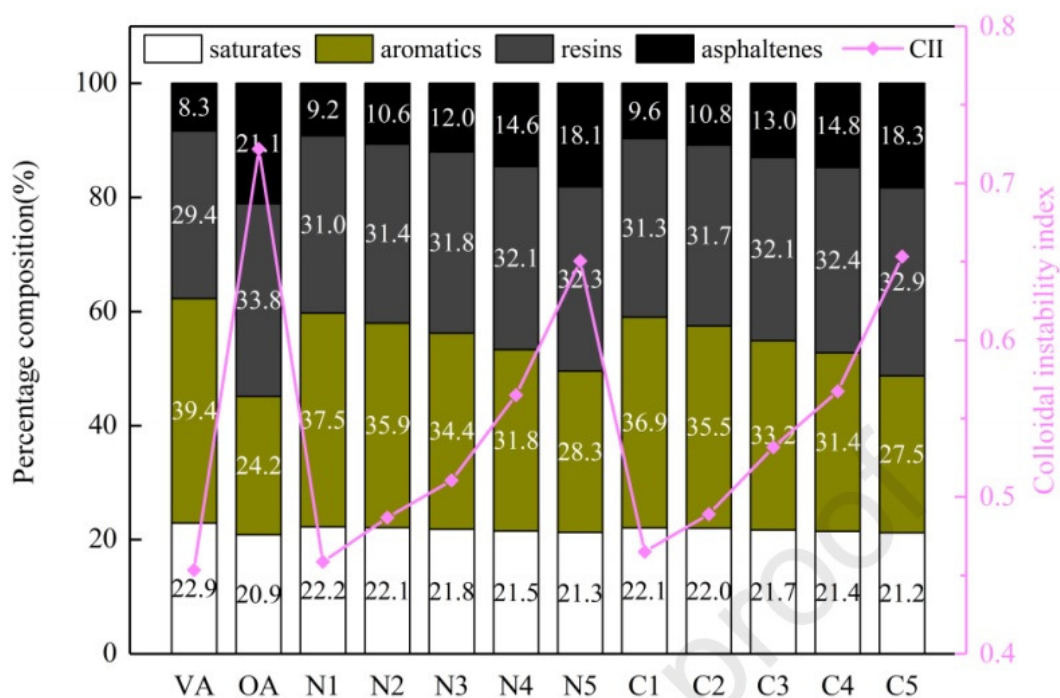


Figure 6. The results of the SARA study and the CII values of the tested bitumen in [16].

Based on the study of the group composition, it is possible to determine the so-called colloidal instability index (CII), which is determined according to the formula (2). A higher index (CII) means lower stability of asphaltenes in the system. As a result, bitumen structure tends to gel – creating more and more complex aggregates of polar compounds, which may accelerate the asphalt pavement degradation process.

$$\text{CII} = \frac{\text{saturates} + \text{asphaltenes}}{\text{aromatics} + \text{resins}} \quad (2)$$

Based on the same studies [16], it was shown that aged bituminous binder has the highest CII index, while bitumen resulting from mixing aged bituminous binder and a selected rejuvenating additive showed a lower CII value. This points to the fact that, for example, properly selected rejuvenating agents can restore the balance of colloidal stability of bitumen that has been subjected to excessively high aging, thus effectively rebuilding the colloidal structure of such a mixture. The reference values for the CII index were not found; in this case, this index should be considered tentative and helpful for the comparative analysis of products. In the literature, the CII values reported most often are for crude oil, where it is assumed that when CII is < 0.7, the crude is stable, and when the CII value is > 0.9, crude oil can be considered unstable, and during its storage and processing the precipitation of asphaltenes may take place [17].

However, it should be noted that when assessing the technical characteristics of a product, one should always take into account a set of parameters covering a wide range of properties, which should preferably be correlated with the performance properties. The purpose of this approach is to exclude the use of single selected indicators or parameters, so as not to exclude a product, such as bitumen, that historically showed high durability in asphalt pavement.

Interventionary studies involving animals or humans, and other studies that require ethical approval, must list the authority that provided approval and the corresponding ethical approval code.

234
235
236
237
238
239
240
241

242
243
244
245
246
247
248
249
250
251
252
253
254
255
256
257

3. Laboratory bitumen aging methods

3.1. Short-term aging

Due to the relatively small changes in bitumen properties during service aging, the assessment of bitumen resistance to aging would be time-consuming without the developed and implemented laboratory methods based on the accelerating bitumen aging phenomenon. Currently, there are both standardized methods of short-term and long-term aging of bitumen as well as new solutions being developed in research centers.

The short-term aging simulation is intended to represent the conditions under which bitumen is hot-processed (*i.e.* $> 150\text{ }^{\circ}\text{C}$) into hot mix asphalt (HMA) until it is incorporated into the pavement. The greatest changes in asphalt among the subsequent technological stages of HMA production occur in the drum of the asphalt mix production plant. Bitumen, stored in a tank at a temperature of $160\text{--}180\text{ }^{\circ}\text{C}$, is introduced into the drum, where it contacts the surface of the hot aggregate. The standard production temperature is $170\text{ }^{\circ}\text{C}$. Then HMA goes to storage silos and from them it is transported by car to the construction site where HMA is poured and compacted at a temperature below $150\text{ }^{\circ}\text{C}$. The aging changes of the binder are influenced by the high temperature after the stage of contact with the aggregate; the storage and transport time during which the HMA is kept at about $170\text{ }^{\circ}\text{C}$ and is in contact with air becomes crucial.

The first common method used to assess changes in bitumen properties after short-term aging is the TFOT (*Thin Film Oven Test*) method. TFOT aging simulation was implemented by Lewis and Welborn in 1940 [18]. It was standardized, among others, by CEN TC 336 as the European standard EN 12607-2 [19]. The determination consists in placing 50 mL of an bitumen sample on a pan with a diameter of 140 mm and a height of 9.5 mm to obtain a thin layer of the binder with a thickness of about 3.2 mm. Next, the samples in the pan are placed on a rotating shelf in an oven for 5 hours at $163\text{ }^{\circ}\text{C}$ under atmospheric pressure. The bitumen sample is exposed to temperature and air.

The TFOT method is used to compare the properties of asphalt in terms of resistance to weight loss due to the evaporation of the lowest boiling hydrocarbons and curing due to heating and contact with atmospheric oxygen.

As a result of this test procedure, aging takes place most intensively on the bituminous binder surface, which is its major drawback (beyond the test time), which in extreme cases can lead to the formation of a hard layer, which can prevent uniform aging. Currently, the TFOT method is used only for soft road bitumen, such as V6000 or V12000, which are classified by determining their viscosity at $60\text{ }^{\circ}\text{C}$, as the value of penetration of these binders is > 400 (given in units of penetration *ie.* 0,1 mm).

265

266

267

268

269

270

271

272

273

274

275

276

277

278

279

280

281

282

283

284

285

286

287

288

289

290

291

292

293

294

295

296

297

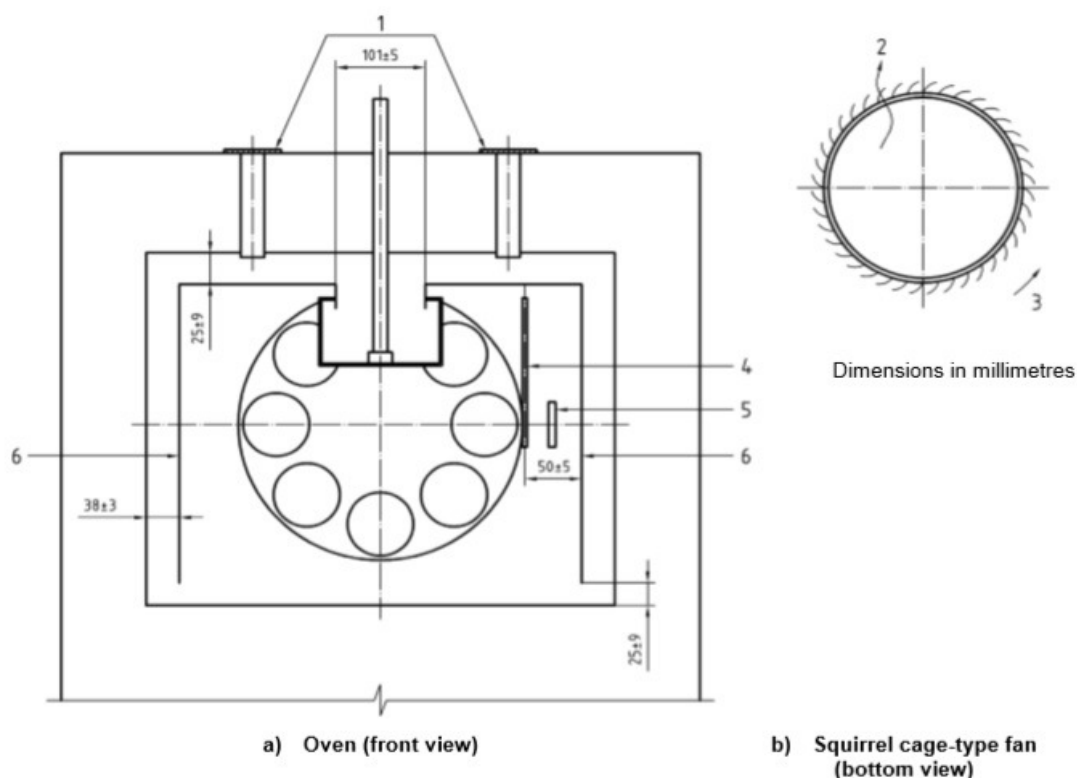
298

299



Figure 7. Photograph of a set of pans and an oven for aging bitumen by the TFOT method [own material].

The evolution of the thin film aging test is the RTFOT (*Rolling Thin Film Oven Test*), a method developed by the California Division of Highways [20]. The aging procedure is described, among others, in the EN 12607-1 standard [21]. Currently, RTFOT is used to simulate the short-term aging of the most widely used road and polymer-modified bitumen. The change primarily involved the container in which the sample is placed from a pan to a glass vessel, which is placed in a special holder. During the RTFOT test, the glass vessel is rotated and the binder can flow when exposed to temperature and air. Due to the smaller sample size, approximately 35 g, the rotating layer of asphalt needs a shorter time to reflect the changes occurring in the process of technological aging in the binder. During the test, the samples are rotated 15 times per minute and the airflow is set at 4000 mL/min. The RTFOT aging temperature is identical to that of the TFOT method, *i.e.* 163 °C. On the other hand, the time of the aging procedure was reduced from 5 hours to 75 minutes according to the European specification and 85 minutes in the case of using the AASHTO T240 [22] or ASTM D2872 [23] standards, *i.e.* laboratory procedures used, among others, in the USA.



Key
 1 upper vents 2 air flow 3 direction of rotation 4 thermometer 5 regulation probe
 6 sheaths

Figure 8. Oven and squirrel cage-type fan for aging by the RTFOT method [EN 12607-1:2014].

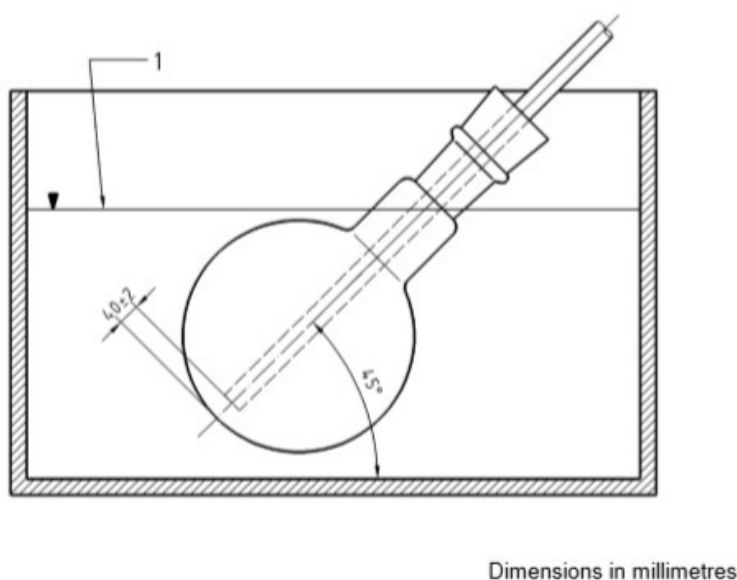
RTFOT aging is the most widely used test method in the world for simulating the short-term aging of bitumen. In the case of testing the resistance to aging of paving grade bitumen, the RTFOT method is sufficient to assess the resistance to aging [24], although the temperature of 163 °C was selected only in terms of the hot technology and does not reflect changes during technological aging in a less energy-consuming warm technology WMA (*warm mix asphalt*).

The greatest difficulties arise when simulating the aging of high-viscosity asphalts, especially those modified with polymers. Bitumen in the vessels does not rotate and, consequently, the thin film is not renewed. Thus, as in the TFOT method, aging occurs on the surface, and the air is not in contact with the entire mass of the sample. Various modifications of the RTFOT test were tried to eliminate this problem, *e.g.* metal rods were introduced into glass containers [25] to generate shear forces and the creation of a thin layer of even highly viscous binders. However, this modification was not accepted by the industry as an effective solution to the problem. Moreover, it is recommended in the EN 14023:2010 standard, specifying polymer modified bitumens (PMB), to increase the RTFOT temperature to 180 °C for hard and highly viscous PMB bitumens. Nevertheless, the temperature increase in the RFTOF method does not fully eliminate the phenomenon of no-rotation of high-viscosity bitumens, thus contributing to an increase in the aging effect of PMBs aged in such a way, which may lead to incorrect assessment of their resistance to high temperature compared to other bitumens aged at a traditionally adopted temperature of 163 °C.

Short-term aging RTFOT undoubtedly has disadvantages in the form of dedication to "hot" technology and difficulties in performing the test for hard or very highly modified bitumens [26]; however, this test allows obtaining samples for further tests that can verify

347 the binders in terms of resistance to technological aging of bitumen. The research con-
348 firmed that the use of two different bitumens in asphalt mix with the same composition,
349 produced under the same conditions, will lead to greater aging in asphalt mix with bi-
350 tumen which showed greater changes in physicochemical parameters after the RTFOT
351 test [27].

352 Another standardized method is the RFT (*Rotating Flask Test*) asphalt aging simulation,
353 initially described in the 1980s in the German standard DIN 52016 [28]. The European
354 standard EN 12607-3 [29] describing the test procedure was developed by the technical
355 committee TC 336 in 2000. The method uses a rotary evaporator into which 100 g of
356 bitumen sample is introduced. The conditions of the RFT aging procedure are 165 °C,
357 time 150 min, and rotation speed of 20 rpm. In addition, air is supplied to the flask at a
358 rate of 500 mL/min. An unquestionable advantage of the RFT method compared to
359 RFTOT is the possibility of obtaining a single homogeneous sample of the aged binder for
360 further tests, *i.e.* 100 g instead of 35 g from one container. Admittedly, as many as 8
361 containers can be used in the RFTOT test, but the removal of bituminous binder from
362 these containers is problematic and if a sample larger than 35 g is required, the test ma-
363 terial from at least two containers must be combined.



364 **Figure 9.** Schematic of RFT aging setup [EN 12607-3:2014].
365
366

367 Other short-term asphalt aging methods are not standardized but only tested and de-
368 veloped by scientists. However, very good data validation with asphalt field measure-
369 ments may result in changing the reference methods to one of the methods described
370 below.

Due to the increasing popularity of long-term aging tests and the need to evaluate the
binder during pavement operation, increasingly larger sample sizes are needed for test-
ing after the technological aging tests. To obtain larger sample sizes (*e.g.* to simulate
long-term aging), a preliminary method based on the RFT test was developed in the USA
[30]. A 200-g sample is placed in a larger flask (1000 mL), and the test is carried out at 165
°C for 210 min. The airflow is set at 2000 mL/min and the rotation of the flask at 20 rpm.
The modified RFT method achieves aging changes similar to the RTFOT method.

Another published modification of the RFT method [31] involves encasing the oil bath to
stabilize the test temperature as well as to be able to use a higher temperature, *e.g.* 200 °C.

380 Furthermore, the flask was placed in the evaporator at an angle of 45° to ensure that the
381 entire sample volume was always below the oil level. The rotation speed was increased to
382 60 rpm and the airflow from 500 mL/min to 4000 mL/min. The modified RFT test using,
383 for example, a test time of 85 min and a 50-g sample, allows for a similar aging effect as
384 the RTFOT method, and after 60 minutes the effect is similar to TFOT. The equipment
385 modified in this way provides greater possibilities for selecting different conditions for
386 accelerated bitumen aging. Depending on the needs and asphalt mix production tech-
387 nology, the conditions of the RFT method can be selected in such a way as to correlate
388 changes in bitumen during heating and contact with air.

389 Another proposed procedure mapping the technological aging of bitumen is Stirred Air-
390 flow Test (SAFT) method, which was supposed to solve the disadvantages associated
391 with the aging of polymer-modified bitumen (insufficient flow in RTFOT containers,
392 formation of a “crust” on the surface of the binder) [32]. The SAFT aging apparatus has a
393 structure that is somewhat reminiscent of bitumen oxidation reactor, as it contains a
394 vessel in which the temperature of the medium is controlled, along with an air or nitro-
395 gen inlet and a stirrer. Comparative tests of the viscosity after SAFT versus RTFOT aging
396 using the developed laboratory conditions performed both on paving grade and modi-
397 fied bitumen samples, revealed a satisfactory correlation [33].

398 Moreover, the advantage of the SAFT method over RTFOT results mainly from two as-
399 pects. Firstly, the time needed to perform the test is reduced to 45 min (including the 15
400 minutes needed to heat the sample to 160 °C), and secondly, the sample is always aver-
401 aged due to its placement in one container and the use of stirring with the installed stir-
402 rer. The test temperature is the same as in the case of RTFOT, *i.e.* 163 °C, the mass of the
403 sample subjected to aging is 250 g, the airflow during the aging period was set at 2000
404 mL/min, and the stirrer speed at 700 rpm. The aging cycle, where the bitumen is exposed
405 to elevated temperature and oxygen in the air, is 30 min.

406 Despite solving the problematic technical aspects of the RTFOT method, the SAFT test
407 was not generally accepted by the industry and science. It was noted in [34] that the
408 SAFT method, carried out using commercially available equipment, ages bitumen to a
409 lower degree, especially in the case of high G* bituminous binders, hence the need to
410 consider whether the procedure time should be extended from 30 to at least 35 minutes.
411 In addition, a sample degassing step has been proposed, because air bubbles trapped in
412 the bitumen affect the values of rheological properties measured. The studies con-
413 ducted by the authors of the report revealed a worsened correlation of changes in the
414 properties of bitumen after aging compared to the RTFOT method and bitumen recov-
415 ered from short-term aged asphalt mix. Ultimately, the SAFT method was not recom-
416 mended for an introduction to the specification.

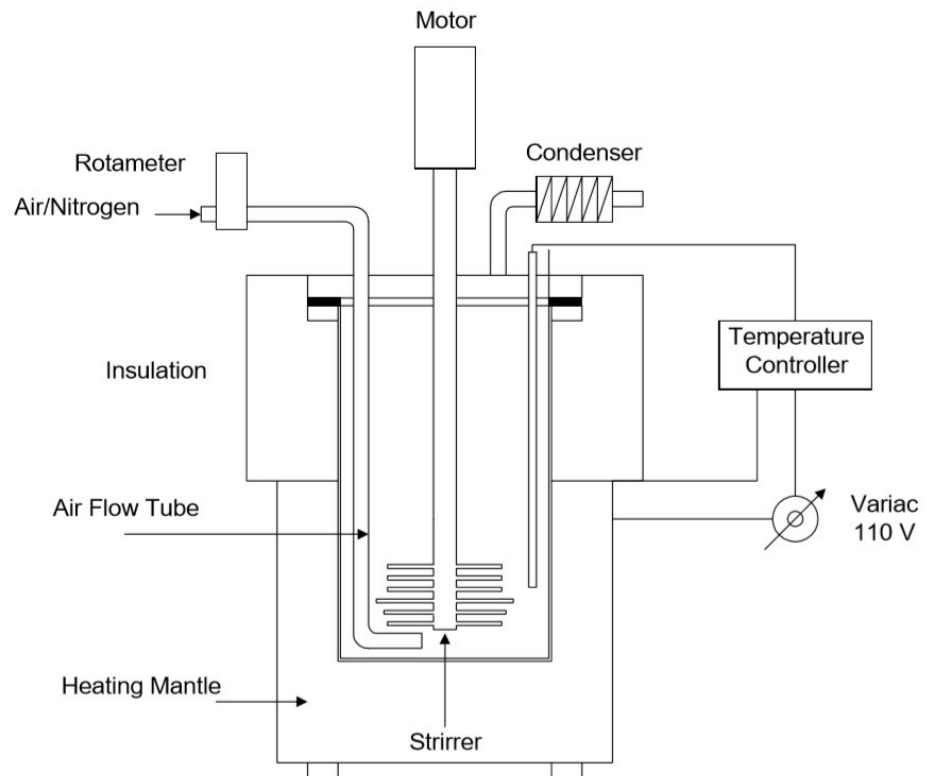


Figure 10. Schematic of the SAFT aging setup [33].

Table 1 summarizes the three most commonly used methods of short-term technological aging of bitumen, covered by the European standards of EN 12607-1, 2, and 3 series. Additionally, different aging conditions are included, provided in the standards used, among others, in North America, *i.e.* AASHTO and ASTM.

Table 1. Conditions for short-term aging of bitumen using the three methods described in European standards.

Method	Aging time [min]	Sample mass [g]	Air flow [mL/min]	Temperature [°C]	Remarks
TFOT	300	50	Without forced circulation	163	Currently used for soft paving grade bitumen, <i>i.e.</i> V6000 acc. to EN 12591
RTFOT	75	35 (8 x 35 g = 280 g)	4000	163	According to AASHTO T240, aging time is 85 min
RFT	150	100	500	165	

3.2. Long-term aging

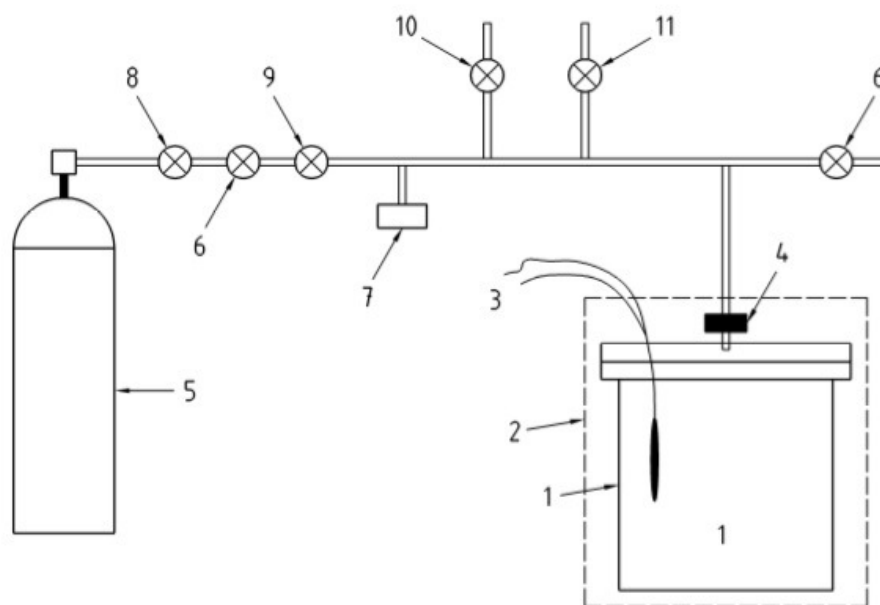
Understanding the behavior of bitumen during technological aging prevents the use of binders with insufficient parameters for pavement construction, whereas to obtain a more complete characterization of changes in bitumen properties after several years of operation, additional tests should be performed. Long-term aging tests are most often performed on bitumen samples that have undergone a short-term aging cycle.

Pressure Aging Vessel (PAV), the most widely used in the world procedure for long-term aging tests, was developed under the SHRP (Strategic Highway Research Program) program in the United States. The entire SHRP research program, completed in 1994 with published reports, was conducted for 5 years and had a budget of \$150 mln. This comprehensive research program was intended to improve the performance of asphalt and concrete products and to develop methods of highway maintenance as well as the issues of long-term durability of road surfaces [35]. Among the significant achievements of the program are the Superpave specifications for asphalt binders and asphalt mixes. The results of the Superpave program led to the publication in the asphalt industry for the first time of bitumen specification related to the functional properties AASHTO M320 [36], which was based on scientific knowledge, in particular the chemistry and mechanics of behavior of construction products such as bituminous binders.

The accelerated long-term aging method in a PAV chamber is described in ASTM D6521 [37] and AASHTO R28 standards [38]. In Europe, however, the method was published as a standard EN 14769, issued in 2005. The procedure involves placing a 50-g sample of asphalt previously subjected to short-term aging in 140-mm diameter trays (TFOT trays can be used). Up to 10 trays can be placed in the PAV apparatus, so – if necessary – a total of about 500 g of asphalt can be simultaneously subjected to the procedure of accelerated long-term aging. Next, the air is supplied to the chamber of the PAV apparatus, which is pressurized to create an overpressure of 2.07 MPa. Aging is



carried out for 20 hours in the temperature range of 90 - 110 °C [39] depending on the grade of bitumen. The lower the penetration or the higher the upper Performance Grade temperature, the higher the aging temperature.



Key

1	pressure ageing vessel	5	compressed air cylinder	9	pressure gauge
2	temperature control	6	needle valve	10	bleed valve
3	thermometer	7	rupture disc	11	pressure release valve
4	quick disconnect	8	pressure regulator		

Figure 11. Diagram of the PAV aging setup [EN 14769-2012].

PAV provides a picture of changes taking place over a longer period of bitumen oxidation. Nevertheless, there are many objections to this aging method since the mechanism of accelerated hardening of the binder does not take into account all the key phenomena that take place during service life aging of pavement [40]. In particular, the high-pressure nature of aging is emphasized, which minimizes the evaporation of hydrocarbons from the binder sample, and the high test temperature, which is unrealistic compared to the pavement temperature and, therefore, under elevated temperature conditions chemical changes in the bitumen which would not occur at lower temperatures may be preferred – this follows from the activation energy of many chemical reactions that can take place in the binder. Additionally, when testing polymer-modified bitumen, there is concern about the possibility of bitumen-polymer separation due to the static nature of the procedure (containers with bitumen do not rotate or spin).

To limit the influence of high temperature on the long-term aging of the bitumen, an alternative procedure called HIPAT (High Pressure Aging Test) based on the PAV method was developed in the United Kingdom [41]. The method uses a lower temperature of 85 °C and extends the aging time to 65 h. Although in the early phase of development the method was indicated as a tool for identifying binders with an increased potential for aging during use, at present HIPAT is not often used in the asphalt industry. The provisions for a special long-term aging procedure at 85 °C are included in the European standard EN 14769 for PAV aging. Currently, only a few

455
456
457
458

459
460

461
462
463
464
465
466
467
468
469
470
471
472
473

MOST WIEDZY

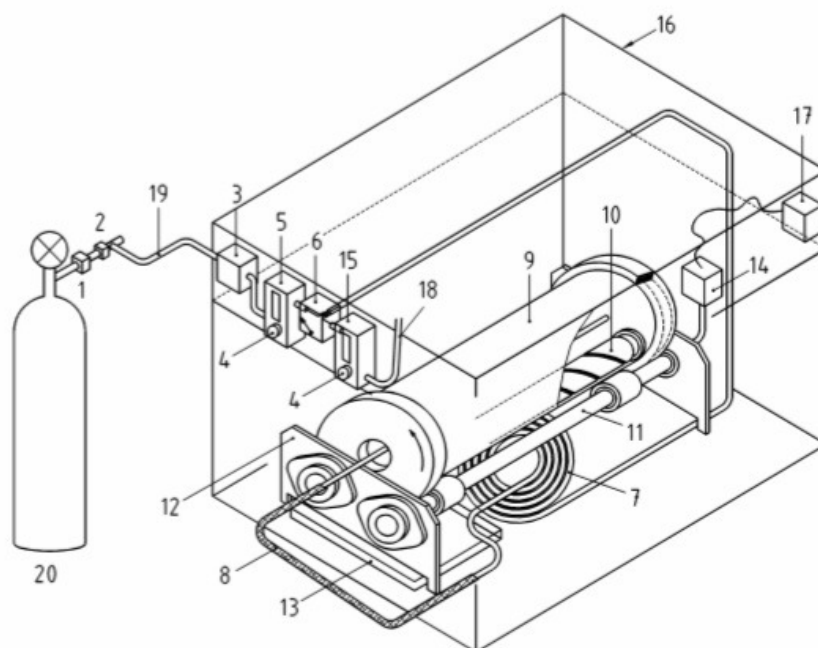


482 studies on the use of this aging method are continued [42], probably due to the time
483 needed to carry out the research using this method.

484 The second main method used for accelerated aging to simulate long-term changes in
485 bitumen is RCAT (Rotating Cylinder Aging Test). The method was developed in Europe
486 at the Belgian Road Research Center [43] at the beginning of the 21st century. The method
487 was standardized in 2007 in CE TC 336 and EN 15323. According to the procedure
488 described in EN 15322, the RCAT test involves placing a sample weighing 525-550 g in a
489 cylinder that has been preheated to the temperature at which the aging will take place.
490 Bitumen is left at this temperature for about 60 min \pm 5 min. During this time, oxygen is
491 not fed to the cylinder and the cylinder is not rotated. After 60 min, in which the asphalt
492 is considered to have reached the RCAT temperature (typically 90 °C), the cylinder is
493 rotated at 1 rpm and oxygen is pumped to the cylinder at 4500 mL/min \pm 500 mL/min.
494 The pressure inside the cylinder is kept at 0.1 MPa. The first bitumen samples are
495 collected after 17 and 65 h to monitor the hardening process. The sample in the RCAT
496 method is aged for 140 \pm 15 min.

497 Moreover, using the RCAT apparatus and changing the aging conditions, an initial
498 short-term aging cycle can be performed [44]; therefore, it is not necessary to conduct
499 several RTFOT tests in to obtain a sample mass of about 500 g for the long-term aging
500 cycle using the RCAT method. In the technological aging cycle, oxygen is replaced with
501 air at a fixed flow rate of 4000 mL/min \pm 200 mL/min, the test temperature is 163 °C, and
502 the aging time is 235 min \pm 5 min. The cylinder is rotated five times faster than in the
503 long-term aging test procedure. After completion of the aging cycle, changes in the
504 properties of the bitumen are determined both by empirical methods (penetration,
505 softening point) and by FTIR spectroscopy identifying changes in the bitumen molecules,
506 which prove that the bitumen aging extent is comparable to that carried out according to
507 the RTFOT procedure.

508 Despite standardization, the European method is not as popular as the PAV method
509 developed for the Superpave program and it is not included as an aging procedure in the
510 specifications of bituminous binders. This is mainly due to the greater availability of PAV
511 aging equipment and the longer test duration for RCAT. However, it should be
512 emphasized that RCAT provides a unique opportunity to perform both short- and
513 long-term aging.

**Key**

- | | |
|---|---|
| 1) Pressure-reducer | 10) Inner grooved stainless steel roller |
| 2) General control needle valve (or excess flow valve) | 11) Driving mechanism to rotate the cylinder |
| 3) Oxygen temperature safety break | 12) Steel stand for all the system |
| 4) Adjusting needle valve | 13) Tray to collect leaking binder |
| 5) Oxygen flow meter | 14) Driving connection (1 r/min or 5 r/min) |
| 6) Inverter air/oxygen | 15) Air flow meter |
| 7) Stainless steel spiral (heating entering gas) | 16) Thermostated oven |
| 8) Stainless steel tube for oxygen supply (enters cylinder almost until the bottom of the cylinder) | 17) Contact for rotation speed (1 r/min or 5 r/min) |
| 9) RCAT ageing cylinder | 18) Air line |
| | 19) Oxygen line |
| | 20) Compressed oxygen bottle |

NOTE In the case of short-term ageing, compressed air bottle is connected through inlet 18 and switching between long-term and short-term conditioning is selected by means of 6.

Figure 12. Schematic diagram of the RCAT ageing apparatus [EN 15323:2017].

A comparison of aging by PAV and RCAT methods shows that the values of bitumen tests made after long-term aging can be comparable. In particular, in the case of bitumen modified with SBS copolymer, when considering the softening point difference parameter, it was shown that PAV aging at 100 °C for 20 h compared to the RCAT procedure at 90 °C for 140 h causes a greater degradation of the polymer. Higher temperature and pressure are important in this case. On the other hand, the polymer-modified asphalt recovered from the exploited asphalt pavement did not show such hardening characteristics as would follow from the PAV procedure. In this case, the analysis of the molecular weight distribution using gel permeation/size exclusion chromatography (GPC/SEC) proves to be helpful in the interpretation of the results. The determinations carried out with GPC/SEC revealed that after 9 years of use of pavement asphalt, there was an even greater degradation of the polymer (decrease in molecular weight) and the compounds resulting from its degradation became a kind of plasticizer,

530 preventing bitumen from strong hardening [45]. The usefulness of GPC/SEC for this
531 type of investigation was described in detail in [46].

532 In Austria, a long-term simulation method called 3xRTFOT was used to specify paving
533 grade bitumen characteristic. The requirement for the softening point after aging RTFOT
534 + 3xRTFOT was defined as the maximum increase of 15 °C with respect to the softening
535 point of the unaged binder. The 3xRTFOT involves performing 3 cycles according to the
536 RTFOT methodology (3x75 minutes), leaving the conditions unchanged. The assessment
537 of changes after long-term aging was introduced to more thoroughly verify the
538 susceptibility of bitumens to overly quick aging. The 3xRTFOT method is sensitive to
539 bitumen containing raw materials from visbreaking installations which, when used in the
540 production of paving grade binders, can cause accelerated and significant adverse
541 changes in asphalt [47]. The process of visbreaking of heavy oil fractions (carried out at T:
542 455-510 °C, and P: 0.3-2 MPa) is considered a mild type of thermal cracking which
543 became very popular in the 1980s. As a result of the conversion of the vacuum residue
544 from the crude oil distillation, additional fuel fractions are obtained. Although the
545 conversion with this technology amounts only to 10 to 25 %, refineries which in those
546 years had a visbreaking installation in their configuration achieved better financial ratios.
547 Bitumen produced with the use of raw materials from the cracking process, such as e.g.
548 made in a visbreaking installation compared to binders produced from distillation
549 fractions, show higher temperature sensitivity and lower resistance to oxidation and,
550 consequently, more pronounced changes during use [48]. The source of accelerated aging
551 is unsaturated hydrocarbons (olefins) and aromatic hydrocarbons, which are generated
552 during thermal cracking at low pressure [49]. The research [50] compared the content of
553 carbon and hydrogen in aromatic structures (C arom. and H arom.) for the vacuum
554 residue (feedstock) and the visbreaking residue (product) using nuclear magnetic
555 resonance (NMR) spectroscopy. As can be seen from the data in Table 2, high molecular
556 weight olefins behave very unstably in petroleum fractions, especially at elevated
557 temperatures. Compounds from this group undergo secondary oxidation reactions,
558 yielding a less useful raw material than the crude vacuum residue.

559 **Table 2.** Measurement of H arom. and C arom. using NMR of residues from Iranian
560 heavy crude oil and Kirkuk crude oil [50].

Parameter	Iranian heavy crude oil		Kirkuk crude oil	
	Vacuum residue	Visbreaking residue	Vacuum residue	Visbreaking residue
H arom.	5.40	7.50 (+ 38.8 %)	5.20	7.90 (+ 51.9 %)
C arom.	25.00	31.00 (+ 24 %)	23.50	31.00 (+ 31.9 %)

The unquestionable advantage of the 3xRTFOT method is the possibility of using the same research equipment for both technological and operational aging tests. However, taking into the real temperature of pavement use compared to the aging process at 163 °C, different physical and chemical transformations take place than would be expected from a method simulating the long-term aging of bitumen.

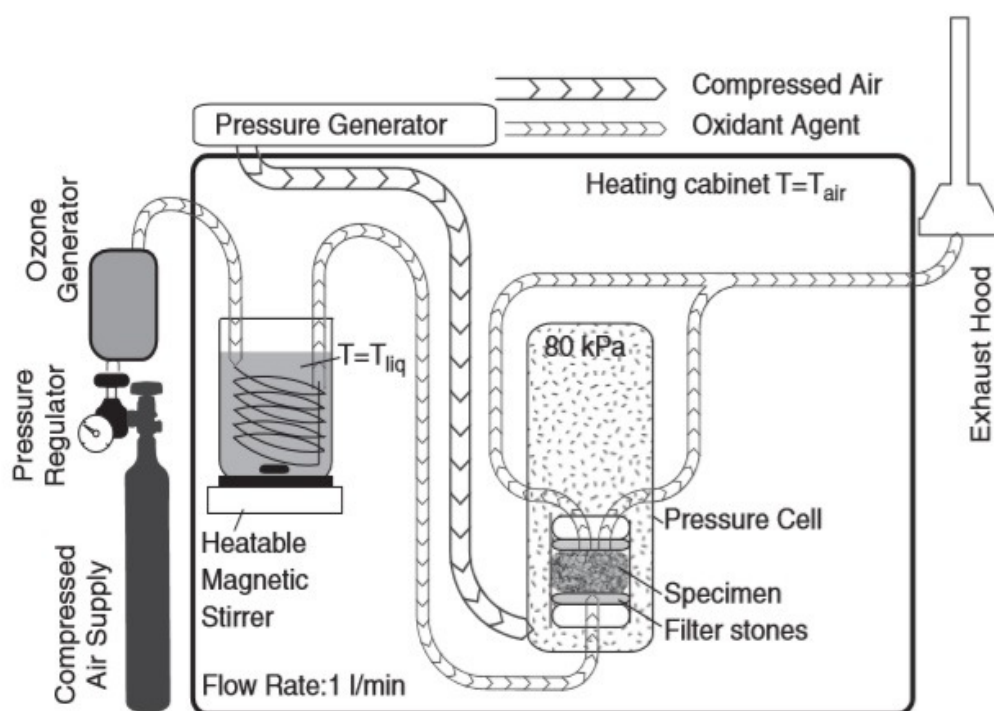
566 A similar approach, the so-called ERTFOT163sra, was presented in South Africa [51],
567 where the time of the RTFOT method to simulate the effect of long-term aging was
568 extended to 325 min. In the meantime, at 205 min, a sample is taken to determine the
569 trend of changes in the characteristics of the bituminous binder. The second version of
570 alternatively modified RTFOT, ERTFOT100sra, additionally had the following
571 parameters changed compared to the RTFOT method: the temperature was reduced to
572 100 °C and the procedure time was extended to 48 h. In addition, metal rods were
573 introduced to aid the spinning of the bitumen layer as described in the fragment with the
574 modified RTFOT method for short-term aging simulation. The study of the correlation
575 of the ERTFOT163sra and ERTFOT100sra methods with PAV performed on asphalts
576 from 7 sources, revealed that aging proceeds more gently at a lower temperature, despite
577 the extended time. On the other hand, RTFOT extended to 325 minutes allows for
578 obtaining changes in bitumen corresponding to the PAV method. It should be
579 emphasized that the ERTFOT163sra method does not require a prior RTFOT test, as
580 within 325 minutes there are aging changes taking into account both short- and long-term
581 oxidative hardening of the bitumen.

582 Currently, the PAV method is often criticized. It has been demonstrated that it does not
583 reflect changes taking place in asphalt during the service life of the road surface. Due to
584 the complexity of the processes occurring in bitumen during pavement exploitation, it
585 appears that none of the methods described above will fully reflect the phenomena
586 taking place in reality [52]. At present, aging procedures are being developed that take
587 into account, in addition to the effects of heat and oxygen as an oxidant, also the effect of
588 UV, moisture and exhaust gases, especially in the case of bitumens used for the wear
589 layer of asphalt mix. In addition, accelerated aging tests are sought to take into account
590 also the characteristics of the filler used in the asphalt mix and its structure. For example,
591 asphalt mix defined as porous asphalt contains a relatively large amount of void space,
592 hence the oxidative aging of such a mix is increased compared to more packed asphalt
593 mix, such as asphalt concrete.

594 To more adequately reflect the wear and tear of bitumen over 5 to 10 years, the Vienna
595 University of Technology developed the VAPro (Viennese Aging Procedure) method
596 [53], which uses conditions similar to the natural aging conditions occurring during their
597 use. The method is an extension of the procedure proposed in the SHRP-A-383 report
598 [54]. The temperature of the VAPro procedure is 60 °C, an overpressure of about 80 kPa,
599 and the flow of air enriched with ozone and nitrogen oxides at the level of 0.9 – 1.1 L/min.
600 Ozone and nitrogen oxides are produced using an ozone generator. The entire long-term
601 aging procedure takes 3 days and is intended to reflect all changes occurring during the
602 short and long term hardening of bitumen.

603 In the VAPro method, unlike the others described, the asphalt mix sample is aged, and
604 then, following the aging cycle, the asphalt is recovered and the tests in parameters are
605 performed for the recovered binder. On the one hand, it is justified, as it takes into
606 account the interaction of asphalt mix components and the type of asphalt mix, on the
607 other hand, it complicates the preparation of the sample and its recovery after aging.

608



609

610

Figure 13. Schematic diagram of the VAPro aging apparatus [53].

611

612

613

614

615

616

617

618

619

620

621

622

623

624

625

626

627

The test results for bitumens after VAPro aging compared to RTFOT + PAV aging differ significantly. Reported changes in binder properties are always greater after the VAPro procedure. In particular, the Austrian procedure provides greater changes than PAV, especially for asphalt samples from less typical sources, and better reflects the changes in the properties of low-temperature binders during operation. In the case of assessment of σ in the bending beam rheometer (BBR), polymer-modified bitumens showed the expected change in σ after long-term aging (VAPro), while for the same samples after RTFOT + PAV procedures the changes were only slight [55].

A drawback of the VAPro procedure is the time necessary to prepare the sample because the sample is not only a binder as in the methods described previously but also a concentrated asphalt mix. As a result, the method takes into account the effect of mineral components and the packing density of the sample, but at the same time increases the requirements for the amount of material, time-consuming mixing of components, and compaction of asphalt mix. In addition, the time of the procedure is also 52 hours longer than in the case of the PAV method.

Table 3 summarizes the most commonly used long-term (service life) aging methods, covered by European EN standards as well as AASHTO and ASTM standards used, among others, in North America.

Table 3. Long-term aging conditions for basic methods standardized in EN, AASHTO and ASTM standards.

632
633
634

Method	Aging time [h]	Sample mass [g]	Gas flow rate [mL/min]	Temperature [°C]	Pressure [MPa]	Remarks
PAV	20	500 (10 x 50 g)	Air is used without forced flow	90 - 110 °C	2.07	110 °C is used to simulate <i>e.g.</i> desert conditions
RCAT	140	525 -550	Oxygen 4500 mL/min	typical 90 °C, max 100 °C	0.1	Cylinder rotations 1 rpm
PAV(H IPAT)	65	500-50(10x50g)	Air is used without forced flow	85 °C	2.07	If 85°C is used, the time should be extended to 65 h.

635
636
637
638
639
640
641
642
643
644
645
646

This review does not cover test methods that take into account the role of UV and moisture in the aging of bituminous binders. These methods are of importance primarily to the bitumen used for the wearing course of road surfaces.

4. Suggestions for the future work

This literature review, taking into account the industry standards used in laboratory practice in Europe and North America, and the authors' experience in testing bitumen binders, allows to propose the following changes with respect to the developed or currently modified methods of bitumen aging:

- a) For short-term aging, differentiation of the aging temperature or the aging time should be used to identify realistic changes to the bitumen during its processing to asphalt mix. For example, when bitumen is used at 180°C, this temperature should be used for the RTFOT procedure or the conditioning time of the sample should be extended with respect to reference parameters.
- b) Correlate the method of short-term aging of bituminous binders and the test conditions with the end use in such a way that the test results recorded after aging provided a realistic reference to the changes occurring in the product during its processing. For example, classify the applications depending on the technological

temperatures into hot, warm, semi-warm or cold technologies and select the appropriate aging parameters for the technologies mentioned.

c) The long-term aging of the bitumen, depending mainly on the chemical properties of the bitumen and climatic conditions, should also differ in relation to the location of the given bitumen in a specific layer of the pavement. Depending on whether the bitumen is used for the wearing course (most exposed to environmental aging) or for the foundation (the lowest asphalt mix layer of the road), it should be subjected to long-term aging under appropriately selected conditions (conditioning time, temperature, air pressure, etc.). Such differentiation would allow the elimination of bitumen most susceptible to changes in the properties of the wearing courses and, at the same time, if the criteria are met, enabling their use for the lower layers of asphalt pavements. The application of these proposals will have an impact on obtaining changes in bitumen similar to the real ones, which is important both in the research aspect and in industrial application. Omitting these issues in product specifications or newly developed bituminous binder formulations in relation to the actual changes taking place in bitumen, when applying them to a given technology and end use, reduces the credibility of the results and conclusions.

5. Conclusions

The aging process of the asphalt binder in the road surface is very complex. It is affected by climatic conditions (temperature, especially extreme temperatures and the number of passes through 0 °C, air humidity, number of hours of sunshine, precipitation, and air pollution), technological conditions (temperature and time of further processing) as well as conditions resulting from its chemical structure (oil source, production technology, additives and modifiers used). Therefore, it has not been possible to develop a method to simulate the actual bitumen aging so far, and this task seems difficult to implement at the moment.

In laboratory practice, the most frequently used test procedures and equipment are in line with the RTFOT methodology in the case of short-term aging and the PAV method for the assessment of changes after long-term aging. This is mainly due to the imposition of these procedures in technical specifications, the availability of laboratory equipment, and the simplicity of laboratory procedures. Other methods are used to a negligible extent, mainly in scientific research or in the validation stages of new promising bitumen aging tests.

An important issue, which is not fully understood with the currently used different bitumen application technologies, is the assumption of one aging temperature in RTFOT (most often it is 163°C). In the case of very hard asphalts, e.g. 10/20 or 20/30, and on the other hand relatively soft asphalts 100/150 or 160/220, the use of the same laboratory aging temperature significantly differs from the temperatures used in the production technology of both hot mix asphalt and warm mix asphalt. The changes recorded under the test conditions often do not correspond to the actual changes taking place during the processing of bitumen using the technology suitable for the production of the product for its intended final application. It seems a better option to use a different temperature or shorten the aging time to improve the assessment of the suitability of a given type or source of bitumen depending on the intended use of a given grade of bituminous binder.

The same applies to the PAV procedure, although compared to RTFOT the choice is most often made between the temperatures of 80, 90, and 100 or 110 °C. The selection is made

701 based on inaccurate criteria, where a temperature of 100 °C is often used with a 20-h
702 conditioning time of the sample in the apparatus. For example, a temperature of 110 °C
703 is used in desert climates with relatively high air temperatures.

704 Undoubtedly, a fairly important aspect is the amount of material that is used in bitumen
705 aging procedures. One aging cycle is often insufficient to fully characterize changes in
706 bitumen properties or to prepare samples of special asphalt mixes. This leads to the need
707 to prepare another series of samples and perform additional aging cycles. Obviously,
708 this is time-consuming and, in the case of the need for quick tests, may introduce errors in
709 the determinations due to the omission of averaging the samples from individual aging
710 cycles.

711 Moreover, the simulation time of long-term aging is long as far as performing the test is
712 concerned. Performing the full bitumen aging cycle using the most popular procedures
713 requires nearly 24 h, because the preparation of the sample for RTFOT takes
714 approximately 30-90 min depending on the consistency of the sample, the RTFOT takes
715 another 75 min, then the preparation of samples for PAV another 30-60 min and
716 performance of PAV usually takes 20 h, followed by the degassing of the samples
717 removed from the PAV apparatus (approximately 60 min).

718 A significant disadvantage of the bitumen aging procedures described in this article is
719 the inability to record changes in bitumen parameters automatically during the aging
720 simulation process. If a test sample has to be collected while the procedure is in progress,
721 it is necessary to pause, draw samples manually, and restart aging to complete the cycle.
722 Arguably, the development of bitumen testing methods should focus on the automation
723 of procedures in which parameters can be dynamically changed with simultaneous
724 recording of the sample properties.

725 New methods of simulation of aging focus on the need to eliminate the above-mentioned
726 inconveniences, but none of the methods described so far has been accepted by scientists
727 or the industry.

728 **Author Contributions:** Czajkowski Paweł: Conceptualization, Methodology, Writing - original
729 draft. Andrzej Przyjazny: Writing - review & editing. Grzegorz Boczkaj*: Conceptualization,
730 Methodology, Writing - review & editing, Supervision, Project administration.

731 **Conflicts of Interest:** "The authors declare no conflict of interest."

732 References

- 733 1. <https://www.gov.pl/web/gddkia> (2020).
- 734 2. <https://www.betonowedrogi.com/aktualnosci/seminarium-drogi-betonowe-trwale-i-niezawodne-rozwiazani-e-15-maja-2019-targi-autostrada-kielce/> (2019).
- 735 3. <https://www.fhwa.dot.gov/policyinformation/statistics/2018/hm12.cfm> (2018).
- 736 4. Coons, Richard Ferguson. An investigation of the hardening of asphalt recovered from pavements of various
737 ages, Georgia Tech Theses and Dissertations, School of Civil and Environmental Engineering Theses and Dis-
738 sertations (1965).
- 739 5. Jing, Ruxin, Aikaterini Varveri, Xueyan Liu, Athanasios Scarpas, and Sandra Erkens. "Laboratory and Field
Aging Effect on Bitumen Chemistry and Rheology in Porous Asphalt Mixture." *Transportation Research Record*
2019. 2673 (3): 365–74. <https://doi.org/10.1177/0361198119833362>.
6. Apostolidis, Panos, Xueyan Liu, Cor Kasbergen, and A. Tom Scarpas.. "Synthesis of Asphalt Binder Aging and
the State of the Art of Antiaging Technologies." *Transportation Research Record* 2017. 2633 (1).
<https://doi.org/10.3141/2633-17>.
7. Lu, Xiaohu, and Ulf Isacsson. "Effect of Aging on Bitumen Chemistry and Rheology." *Construction and Building*
Materials. 2002 16 (1): 15–22. [https://doi.org/10.1016/S0950-0618\(01\)00033-2](https://doi.org/10.1016/S0950-0618(01)00033-2).

- 748 8. K. Liliana, G. Guido, Characterization of Polymers and Plastics (pellets, powders and films) by the Thermo
749 Scientific FLASH 2000 Elemental Analyzer, *Application note*, **2016**. 42230 1-5.
- 750 9. ASTM-D4124-2009 (2018) Test Method for Separation of Asphalt into Four Fractions.
- 751 10. Corbett, Luke W. "Composition of asphalt based on generic fractionation, using solvent deasphalting, elu-
752 tion-adsorption chromatography, and densitometric characterization." *Analytical Chemistry* 41, no. 4 (1969):
753 576-579.
- 754 11. Hunter, Robert N., Andy Self, John Read, and Elizabeth Hobson. The shell bitumen handbook. London, UK:
755 ICE Publishing, **2015**.
- 756 12. Lesueur, Didier. "The colloidal structure of bitumen: Consequences on the rheology and on the mechanisms of
757 bitumen modification." *Advances in colloid and interface science* 145, no. 1-2 (2009): 42-82.
- 758 13. Jones IV, David R., and Thomas W. Kennedy. "The asphalt model: results of the SHRP asphalt research pro-
759 gram." *Transportation Research Board VTI Rapport A 372* (1991): 83-90.
- 760 14. Lewis, R. H., and J. Y. Welborn. "The Properties of the Residues of 50-60 and 85-100 Penetration Asphalts from
761 Oven Tests and Exposure." *Public Roads* (1941).
- 762 15. Koyun, Ayse, Johannes Büchner, Michael P. Wistuba, and Hinrich Grothe. "Rheological, spectroscopic and
763 microscopic assessment of asphalt binder aging." *Road Materials and Pavement Design* (2020): 1-18.
- 764 16. Yang, Chao, Jianwei Zhang, Fei Yang, Ming Cheng, Yafei Wang, Serji Amirkhania, Shaopeng Wu, Minghua
765 Wei, and Jun Xie. "Multi-scale performance evaluation and correlation analysis of blended asphalt and recy-
766 cled asphalt mixtures incorporating high RAP content." *Journal of Cleaner Production* (2021): 128278.
767 doi:10.1016/j.jclepro.2021.128278.
- 768 17. Guzmán, R., Ancheyta, J., Trejo, F., & Rodríguez, S. Methods for determining asphaltene stability in crude oils.
769 *Fuel* (2017), 188, 530–543. doi:10.1016/j.fuel.2016.10.012.
- 770 18. Lewis, R. H., and J. Y. Welborn. "Report on the Properties of the Residues of 50-60 and 85-100 Penetration
771 Asphalts from Oven Tests and Exposure." In *Proceedings, Association of Asphalt Paving Technologists*, (1940) vol.
772 11, pp. 86-157.
- 773 19. EN 12607-2 Bitumen and bituminous binders - Determination of the resistance to hardening under influence of
774 heat and air - Part 2: TFOT method.
- 775 20. Hveem, Francis N., Ernest Zube, and John Skog. "Proposed new tests and specifications for paving grade as-
776 phalts." In *Association of Asphalt Paving Technologists Proceedings*, (1963), vol. 32.
- 777 21. EN 12607-1 Bitumen and bituminous binders - Determination of the resistance to hardening under influence of
778 heat and air - Part 1: RTFOT method.
- 779 22. AASHTO T 240, Standard Method of Test for Effect of Heat and Air on a Moving Film of Asphalt Binder
780 (Rolling Thin-Film Oven Test).
- 781 23. ASTM D2872-19, Standard Test Method for Effect of Heat and Air on a Moving Film of Asphalt (Rolling
782 Thin-Film Oven Test), ASTM International, West Conshohocken, PA, **2019**, www.astm.org.
- 783 24. Erkens, Sandra, Laurent Porot, Ronald Glaser, and Charles Glover. REVIEW OF ASPHALT (CONCRETE)
784 AGING TESTS IN THE US AND EUROPE (2016).
- 785 25. Bahia, H. U., D. I. Hanson, M. Zeng, H. Zhai, M. A. Khatri, and R. M. Anderson. "NCHRP Report 459: Char-
786 acterization of modified asphalt binders in Superpave Mix Design." *TRB, National Research Council, Washington,*
787 *DC* (2001): 1-45.
- 788 26. Shalaby, Ahmed.. "Modelling Short-Term Aging of Asphalt Binders Using the Rolling Thin Film Oven Test."
789 *Canadian Journal of Civil Engineering* (2002), 29 (1): 135–44. <https://doi.org/10.1139/I01-086>.
- 790 27. Erkens, Sandra, Tom Scarpas, Ronald Blab, Ron Glaser, Charles Glover, Markus Oeser, Laurent Porot, and
791 Hilde Soenen.. "Aging Symposium Proceedings FINAL." *Aging Symposium Proceedings*, (2014).
- 792 28. DIN 52016:1980-12 Prüfung bituminöser Bindemittel; Thermische Beanspruchung im rotierenden Kolben.
- 793 29. EN 12607-3 Bitumen and bituminous binders - Determination of the resistance to hardening under influence
794 of heat and air - Part 3: RFT method.
- 795 30. Robertson, Raymond E., Jan F. Branthaver, P. Michael Harnsberger, J. Claine Petersen, Samuel M. Dorrence,
796 John F. McKay, T. Fred Turner et al. *Fundamental properties of asphalts and modified asphalts*, volume I: Interpre-
797 tive report. (2001), No. FHWA-RD-99-212,

- 798 31. Sirin, Okan, Chuang Tsair Shih, Mang Tia, and Byron E. Ruth. "Development of a Modified Rotavapor Appa-
799 ratus and Method for Short-Term Aging of Modified Asphalts." *Transportation Research Record*, no. 1638: (1998),
800 72–81. <https://doi.org/10.3141/1638-09>.
- 801 32. Glover, Charles J., Amy Epps Martin, Arif Chowdhury, Rongbin Han, Nikornpon Prapaitrakul, Xin Jin, and
802 James Lawrence. "Evaluation of Binder Aging and Its Influence in Aging of Hot Mix Asphalt Concrete: *Liter-*
803 *ature Review and Experimental Design*, (2009).," no. 2: 68. <http://tti.tamu.edu/documents/0-6009-1.pdf>.
- 804 33. Vassiliev, Nikolai Y., Richard R. Davison, and Charles J. Glover.. "Development of a Stirred Airflow Test Pro-
805 cedure for Short-Term Aging of Asphaltic Materials." *Transportation Research Record*, (2002), no. 1810: 25–32.
806 <https://doi.org/10.3141/1810-04>.
- 807 34. Ramon Bonaquist, and David A. Anderson.. Investigation of Short-Term Laboratory Aging of Neat and Mod-
808 ified Asphalt Binders. *Investigation of Short-Term Laboratory Aging of Neat and Modified Asphalt Binders*. (2011),
809 <https://doi.org/10.17226/14613>.
- 810 35. Kennedy, Thomas W, Gerald A Huber, Edward T Harrigan, Ronald J Cominsky, Charles S Hughes, Harold
811 Von Quintus, and James S Moulthrop. 1994. Superior Performing Asphalt Pavements (Superpave): The Prod-
812 uct of the SHRP Asphalt Research Program. Report SHRP-A-410. Strategic Highway Research Program, Na-
813 tional Research Council, Washington D.C.
- 814 36. AASHTO M 320, Standard Specification for Performance-Graded Asphalt Binder.
- 815 37. ASTM D6521-19a, Standard Practice for Accelerated Aging of Asphalt Binder Using a Pressurized Aging
816 Vessel (PAV), *ASTM International*, West Conshohocken, PA, 2019, www.astm.org.
- 817 38. AASHTO R 28, Standard Practice for Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel
818 (PAV).
- 819 39. EN 14769: Bitumen and bituminous binders. Accelerated long-term aging conditioning by a Pressure Aging
820 Vessel (PAV), (2012).
- 821 40. Qin, Qian, John F. Schabron, Ryan B. Boysen, and Michael J. Farrar. 2014. "Field Aging Effect on Chemistry and
822 Rheology of Asphalt Binders and Rheological Predictions for Field Aging." *Fuel* 121 (2013): 86–94.
823 <https://doi.org/10.1016/j.fuel.2013.12.040>.
- 824 41. Airey, G. D.. "State of the Art Report on Aging Test Methods for Bituminous Pavement Materials." *Interna-*
825 *tional Journal of Pavement Engineering* (2003), 4 (3): 165–76. <https://doi.org/10.1080/1029843042000198568>.
- 826 42. Widyatmoko, I, M.W. Heslop, and R.C. Elliott. "Viscous to Elastic Transition Temperature and the In Situ
827 Performance of Bituminous and Asphaltic Materials." *Journal of the Institute of Asphalt Technology*, (2005).
- 828 43. Short-and-long-term aging of bituminous binders – simulation with the RCAT method, A. Verhasselt, PRO 28:
829 6th International RILEM Symposium on Performance Testing and Evaluation of Bituminous Materials
830 (PTEBM'03).
- 831 44. EN 15323:2007 Bitumen and bituminous binders. Accelerated long-term aging/conditioning by the rotating
832 cylinder method (RCAT).
- 833 45. Lu, X., H. Soenen, and O. V. Laukkanen. "Aging of Bituminous Binders in Asphalt Pavements and Laboratory
834 Tests." *Bearing Capacity of Roads, Railways and Airfields - Proceedings of the 10th International Conference on the*
835 *Bearing Capacity of Roads, Railways and Airfields*, BCRRA 2017, no. (2018): 273–80.
836 <https://doi.org/10.1201/9781315100333-40>.
- 837 46. Kosińska, Judyta, Grzegorz Boczka, Grażyna Gałęzowska, Joanna Podwysocka, Andrzej Przyjazny, and Ma-
838 rian Kamiński. "Determination of Modifier Contents in Polymer-Modified Bitumens and in Samples Collected
839 from the Roads Using High-Performance Gel Permeation/Size-Exclusion Chromatography." *Road Materials and*
840 *Pavement Design* (2016), 17 (3): 547–62. <https://doi.org/10.1080/14680629.2015.1094398>.
- 841 47. Dasek, Ondrej, Svatopluk Stoklasek, Pavel Coufalik, Petr Hyzl, and Michal Varaus.. "Thermooxidative Prop-
842 erties of Bituminous Binders in Relation to Their Inner Chemical Compatibility Determined by Single Point
843 Precipitation Titration." *Road Materials and Pavement Design*, (2017): 118–30.
844 <https://doi.org/10.1080/14680629.2017.1304254>.
- 845 48. Giavarini, Carlo. "Visbreaker and Straight-Run Bitumens." *Fuel*, (1984), 63 (11): 1515–17.
846 [https://doi.org/10.1016/0016-2361\(84\)90217-5](https://doi.org/10.1016/0016-2361(84)90217-5).

- 847 49. Mazzoni, Giorgia, Edoardo Bocci, and Francesco Canestrari. "Influence of Rejuvenators on Bitumen Aging in
848 Hot Recycled Asphalt Mixtures." *Journal of Traffic and Transportation Engineering (English Edition)* (2018), 5
849 (3): 157–68. <https://doi.org/10.1016/j.jtte.2018.01.001>.
- 850 50. Giavarini, Carlo, and Stefano Maregrande.. "Characterization Studies on Visbreaker Residues and Bitumens."
851 *Fuel Science and Technology International* (1989), 7 (8): 1121–38. <https://doi.org/10.1080/08843758908962282>.
- 852 51. Muller, Johan, Kim J Jenkins, and Johan Muller. n.d. "The Use of an Extended Rolling Thin Film Aging Method
853 As an Alternative" 1–14.
- 854 52. Erkens, Sandra, Laurent Porot, Ronald Glaser, and Charles Glover. 2016. REVIEW OF ASPHALT (CON-
855 CRETE) AGING TESTS IN THE US AND EUROPE.
- 856 53. Steiner, Daniel, Bernhard Hofko, Markus Hospodka, Florian Handle, Hinrich Grothe, Josef Füssl, Lukas
857 Eberhardsteiner, and Ronald Blab "Towards an Optimised Lab Procedure for Long-Term Oxidative Aging of
858 Asphalt Mix Specimen." *International Journal of Pavement Engineering* . (2016), 17 (6): 471–77.
859 <https://doi.org/10.1080/10298436.2014.993204>.
- 860 54. Bell, C a, Y Abwahab, M E Cristi, and D Sosnovske. 1994. "Selection of Laboratory Aging Procedures for As-
861 phalt-Aggregate Mixtures," 92.
- 862 55. Maschauer, Daniel, Daniel Steiner, Johannes Mirwald, Bernhard Hofko, and Hinrich Grothe.. Viennese Aging
863 Procedure – Behavior of Various Bitumen Provenances. RILEM Bookseries. (2019), Vol. 20. Springer Interna-
864 tional Publishing. <https://doi.org/10.1007/978-3-030-00476-7-11>.