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Synthesis of Asphalt Binder Aging and the State-of-the-Art of Anti-Aging Technologies

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Abstract: Aging is the accumulation process of diverse detrimental changes in molecular structures with advancing age. Resistance to aging is termed durability. Complex molecular systems such as asphalt binder need to be protected against aging. In this paper, a state-of-the-art review of anti-aging technologies used to prohibit or to rejuvenate the aged asphaltic materials is provided. The kinetics of molecular structures during aging and the group of molecules affected mainly are discussed. The latest developments on anti-oxidation and rejuvenation technologies are given as well showing the impact of anti-aging technologies for the asphalt binder.

1. INTRODUCTION

The transportation industry consumes approximately 32.6% of the total energy produced in the European Union and almost 28% in the United States. In parallel with the increasing cost and the strong global demand for low prices of the paving materials and operations, the rapid aging of asphalt pavements due to the aggressive environmental conditions is becoming a pragmatic concern for the whole transportation industry. Avoiding the aging of asphalt binder or preventing the undesirable effects of ultimate degradation of asphalt mixes after certain time are among the major topics in which governmental authorities and infrastructure contractors have focused. Strategies, such as preventive maintenance techniques and reconstructive treatments of asphalt pavements, have been deployed in the last years to deal with the aging phenomena of asphaltic materials. Also, the utilization of additives as the countermeasure to prohibit aging of asphaltic materials (i.e., anti-oxidants) and to restore materials' characteristics (i.e., rejuvenators) shows significant benefits in these efforts.

Asphalt binder (AB) is composed of an extremely large number of different types of organic molecules ranging from paraffins to alkyl polyaromatics containing heteroatoms of nitrogen (≤ 2%), oxygen (≤ 2%), sulphur (≤ 6%) and traces of metals such as vanadium and nickel. These molecules are separated in categories based on the chemical reactivity and the polarity of organic molecules. The dispersion of polar organic molecules in a medium of less polar molecules and their interaction are highly associated with the performance-related properties of ABs and their susceptibility under oxidation. When the material is oxidized, the state of molecular dispersion within the binder alters and new polar molecules are produced.

Several studies have reported on the oxidation chemistry of AB, the main factors influencing aging and how aging can be addressed using chemical additives and anti-aging technologies. In this paper, focus was given to combine information of the most valuable researches which were validated for several times for the aged ABs and the anti-aging technologies. The current and concise state-of-the-art review on aging and anti-aging is provided with highlighting the chemistry of AB and the chemical interaction of anti-aging additives on them.

2. AGING OF ASPHALT BINDER

2.1 Functional groups and fractions of aging

A lot of effort has been given to get information on the organic molecular groups in virgin and aged ABs where new functional groups are formed because of the chemical interaction mainly between oxygen and organic molecules of binder. Among the other groups, the heterogeneous functional groups in binders have been mentioned with the largest impact on properties (1). The heteroatom-containing groups in ABs were identified as highly polar and more interacting groups. These are made-up mainly from large organic molecules; (i) carboxylic acids, (ii) anhydrides, (iii) ketones, (iv) 2-quinolone types, (v) sulfoxides, (vi) pyrrolic and (vii) phenolic types.

Sulphur is the most present polar atom and it is displayed in molecules as sulphides, thiols and sulfoxides. Oxygen has appeared in the form of ketones, phenols and carboxylic acids.

Pyrrolic, pyridic and 2-quinoline structures are also formed based on nitrogen. The moieties groups formed naturally in AB are carboxylic acids, phenolic, pyrrolic and 2-quinolone-type groups which are hydrogen bonding functional groups.

In terms of aging, oxygen-containing chemical functional groups are formed after reactions with highly polar molecules, such as polar aromatics. Less reactive molecules with low polarity or nonpolar elements suffer less or no aging (oxidation). Mainly sulfoxides (2) and ketones (3) are produced with lesser amounts of dicarboxylic anhydrides and carboxylic acids at a later time after aging (4). Previous researches have shown that sulfoxides are formed at a much faster rate than ketones (2). Moreover, ketones are formed at the benzylic carbon position and hydrogen on the tertiary benzylic carbon is very reactive and thus easily removed during oxidation (3, 5). Moreover, studies on chemical reactions of aromatic molecules in ABs reported that in most of the cases the hydrocarbon oxidation reaction is finished after the ketone formation. Anhydrides are resulted directly by the two adjacent benzylic carbon moieties of aromatics (4).

Due to the highly complex molecular structure of AB it is almost impossible to conduct detailed chemical analysis. Previous works carried out to analyze the chemical composition and the functional groups in AB using different techniques such as ultraviolet spectroscopy (UV), infrared spectroscopy (IR), nuclear magnetic resonance (NMR) and mass spectroscopy (MS) approved that difficulty (6). Thus, nowadays techniques able to identify different elements according to their molecular size, reactivity, solubility and polarity are introduced. One of them is the separation technique SARA which separates various fractions and molecular groups based on their polarity into saturates, aromatics, resins and asphaltenes (SARA). The molecular weight of the fractions increase as saturates ≤ aromatics ≤ resins ≤ asphaltenes (7).

The saturate part of AB is non-polar, linear, branched and/or cyclic saturated hydrocarbons. The aromatic fraction is more polar than saturates owing to the contained aromatic rings. Similarly, resins and asphaltenes are polar. Resins are soluble with heptanes or pentane while asphaltenes are insoluble in heptanes. In particular, the fractions of saturates (i.e., paraffins, napthenes and mix of two), aromatics (i.e., mix of paraffin, napthenes and aromatics with sulphur components) and resins (i.e., multi-ring aromatics structures and heteroatoms) consist one category which is named maltenes and together represent the medium solution of asphalt. The non-soluble fraction is the asphaltenes with different molecules (i.e., paraffins, napthenes and polycyclic aromatic structures). Asphaltenes are characterized of weak molecular interactions and they have been identified as the major responsible factor for viscosity increase (6). Moreover, waxes are present in AB after distillation and they are associated with the saturate fraction.

Studies of different fractions of AB show that saturates, as nonpolar hydrocarbon molecules, display weak interaction forces leading to those molecules to demonstrate low viscosity behavior. On the other hand, aromatic ring systems are usually polar and their molecular interactions are very strong explaining thus the loss of sufficient mobility of molecules and subsequently the relatively high viscosity of asphaltenes and aromatics. Furthermore, resins which include polar aromatics demonstrate the highest viscosity among the fractions (8). This description of polarity and the associated performance of molecules in AB has a direct link with the molecular interactions and the performance during the aging.

The amount of polar functional groups is increasing during the AB aging resulting reduction of molecular flow and kinetics. The material becomes stiffer with increased viscosity and reduced phase angle and susceptible under various stresses. However, the composition of molecules differs among different ABs and for this reason researches were conducted to identify which is the most important element correlated with the AB viscosity. It was concluded that asphaltenes, which are the most polar ABs components (9) and ketones

(10-13) display good correlations between their content and the viscosity during aging. Also, it is reported that asphaltenes formed during aging have similar impact on ABs viscosity as asphaltenes originally presented in neat AB (14). Moreover, many researches showed also interest about the compatibility and dispersibility of asphaltenes in ABs (13, 15, 16).

2.2 Kinetics of aging

Due of the fact that the alteration of AB composition during aging is dependent on the type and the material source, it is important to consider the reaction kinetics during aging for each AB. As mentioned before, during AB aging major products at the initial stages of oxidation are ketones and sulfoxides. The rate of formation of these products is characterized as less at later stages when carboxylic acids and dicarboxylic anhydrides being formed (4, 11, 13, 17, 18). The rapid rate of sulfoxide formation at the beginning of aging and the later steady state concentrations depends also on the temperature. In particular, it has been reported that the rate of sulfoxide formation during the initial stage of oxidative aging is higher than ketone formation rate at ambient temperatures. Moreover, at lower temperatures and at the very beginning of aging, only sulfoxides are formed (11, 17, 19, 20). It is important to note that the total concentration of sulfoxide and ketones at the end of the initial oxidation stage is about the same regardless the temperature and the relative amounts of each component (6). However, temperature, oxygen concentration and other environmental conditions consist of a territory of research which is discussed in more details in the next sub-chapter.

From the mechanistic point of view, the AB viscosity increases with increasing amounts of ketones and sulfoxides. Ketones have been shown good correlation with the viscosity increase during long-term oxidation in contrary with those that appeared to demonstrate weak relationship with the viscosity alteration. Studies of oxidized AB examined the correlation of ketones and sulfoxides contents during aging with the fraction of maltenes and asphaltenes in asphalt. When the material was oxidized the fraction of maltenes decreased and that of asphaltenes increased respectively, resulting in parallel a linear correlation of ketones content with asphaltenes concentrations. Furthermore, it is concluded that the highest amount of ketones formed during oxidation were derived from resinous fractions forming large parts of polar aromatics. Also, sulfoxides which are derived from oxidation of sulphides are the less polar fractions and they are not correlated with the formation of asphaltenes. After initial oxidation, the increase of viscosity is not associated by the polarity of ketones or sulfoxide group of molecules but by the large agglomerated molecular domains formed because of the polarity changes of these groups. These agglomeration domains have been recognized as products causing the insufficient mobility (19). Furthermore, the ketones formed during AB aging are concentrated in the asphaltene fractions.

About the oxidation aging kinetics, several models and mechanisms were proposed through the years in order to predict the reaction rate and the mechanical degradation of aged AB (21-23). Proposed reaction mechanisms and possible oxidation pathways give illustrated images of the formed components and the factors that may address catalysis of aging. Oxycyclic reaction mechanism (24), free radical chain reactions (1, 25) and dual sequential asphalt binder oxidation mechanism (17, 20, 23) are among these mechanisms as well.

2.3 Environmental parameters of aging

Aging of AB is normally seen as a function of environmental conditions. Several environmental parameters are believed to play a role in aging phenomena and they are identified as follows.

Oxygen (O_2)

Oxygen is believed to be the key influencing parameter for the aging of AB. It has been shown in numerous studies that oxidative aging results in an increase of the carbonyl content altering the visco-elastic properties of ABs (26-36). Aging normally combines oxygen and elevated temperature. Elevated temperature might only catalyse the oxidation reaction but it could also introduce physical changes, which could be referred to as physical aging.

The oxidation process involved in aging is only partially understood. It is believed that oxygen diffuses through AB and undergoes reaction with some moieties within. The intrinsic chemical reactivity of ABs control mainly the long-term hardening of binder because of oxygen presence. The products of the slow reaction process of oxidative aging normally are represented by sulphoxides, carbonyls, ketones and carboxylic acids (6, 9, 31, 32, 37). In addition to oxidative products, also hydrogen abstraction and polymerisation due to the formation of oxygen radicals have been mentioned (35).

Nevertheless, the real mechanism of these chemical reactions is not clear and for this reason many attempts have been made to correlate the chemical processes of oxidative aging with structural changes of AB (32, 35). One possible explanation is that the oxidative products are more polar than the surrounding moieties and because of the rearrangement of the colloidal structure of binder, the AB viscosity increases. Others propose that the increase in molecular weight is related to cross-linking of molecules during oxidative aging by creating moieties networks which inhibit binder to flow. However, their proof is not that elaborate.

Moisture

The effect of moisture on the process of AB aging has not been frequently documented. Some papers reported the influence of moisture on the oxidative aging phenomenon of AB and they mentioned that the presence of moisture increases the rate of oxidative aging (38). The impact of moisture however does not appears to be that strong as oxygen and the differences in carbonyl formation are relatively small (39).

The presence of water mainly accelerates the aging process such as temperature which catalyses the oxidation reactions as well. This can be explained by the fact that the moisture may disrupt the colloidal structure of binder resulting the alteration of oxygen solubility and subsequently the oxidation rate. On the other hand, another theory suggests that moisture provides a source of hydrogen atoms which can react with free radicals produced during molecular alteration of AB due to aging, preventing thus the radicals polymerization. During this process, higher conversion of maltenes happens (40). Moreover, a recent study of moisture-AB interaction indicates that the effect of moisture on aging and hardening of AB is pressure dependent showing also direct relationship between the different types of ABs and the reaction rates (41).

Ultra Violet radiation (UV)

For many materials exposed to sunlight it is known that UV is able to cause molecular damage to organic molecules. The energy level of UV light generally is high enough to create radical moieties that are very reactive towards other moieties in the vicinity. Consequences of UV radiation therefore are spontaneous oxidation at relative low-temperatures and photo-induced polymerisation at high-temperatures. Both processes will most probably result in similar products as are obtained by exposure to oxygen and high temperatures.

Most probably UV catalyses the oxidative reaction in the presence of oxygen and its effect on aging rate is mainly source dependent. Investigation on the effect of UV radiation on the penetration depth of asphalt has shown that the UV penetration into AB was a function of the depth and only films below of 100 μm were affected (28). Another research reports that in the presence of UV oxidative aging is accelerated, especially in low-temperatures (9). However

UV stimulated oxidative aging shows only a relative small contribution when compared to the effect that standard temperature stimulated oxidative aging causes (34).

Temperature
Temperature is solely used for catalytic purposes to accelerate aging processes imposed by other parameters and it is always used in combination with other potential influencing factors such as oxygen, moisture and UV. Apart from a single published report (42), no control studies were conducted in which temperature was imposed without the presence of the other factors to point out the changes, such as morphological and phase changes, temperature might have on ABs' properties.

3. ANTI-AGING TECHNOLOGIES

3.1 Anti-oxidants

Aging inhibitors or anti-oxidants are used in order to minimize the aging potential and to improve the durability of AB. Nowadays, chemical antioxidants such as amines, tellurium and selenium oxides, lead, zinc dithiocarbamates and dibutyl-dithiocarbamates, styrene-butadiene-styrene and styrene-b-butadiene, hydrate lime, lignin, imidazolines of rapeseed oil and oleic acids have been widely studied for this purpose.

Studies on effectiveness of sodium hydroxide comparing dithiocarbamates showed that sodium hydroxide demonstrates very effective reactivity for prohibiting oxidative aging of AB because of the fact that it increases the dispersibility of asphaltenes by breaking up hydrogen bonding (43). Others approved that zinc dialkyldithiophosphate has been made to enhance the durability of AB by retarding the oxidation through inhibition of peroxides and radical scavenging (44). In this study, lead antioxidant appears to be more effective than zinc. Furthermore, combination of furfural and dilaurylthiodipropionate could further improve the oxidative aging resistance at low and high temperatures (45). Also, introduction of montmorillonite appeared to improve the physico-mechanical properties of AB against oxidative aging (46). Research on the reduction of carbonyl and sulfoxide groups in aging asphalts utilizing sodium borohydribe ($NaBH_4$) has been carried out as well indicating improvement on oxidation resistance (47).

Another performance enhancer which delays aging and thus increases the service life of asphalt are layered double hydroxides (LDHs). LDHs are anionic layered materials formed by interlayer anions and laminates with a positive charge and are widely used as catalysts, catalyst supports, electrodes and polymer additives (48-52). LDH antioxidant is also well known as hydrotalcite-like compound with supramolecular structures, which are assemblies consisting of two or more molecules stabilized by intermolecular bonds. LDH effectiveness is derived by its capability to prevent oxygen infiltration. Also, the metallic layer and the anions on the interlayer of LDHs can absorb UV waves increasing thus the resistance of AB against UV radiation. Results from an analysis of the anti-oxidation impact of AB with LDH and 4 (3.5-di-tert-butyl-4-hydroxy) styrene-acrylic acid ester of pentaerythitol (Irganox 1010) showed good resistance on oxidative and ultraviolet aging peptizing asphaltenes (52). Similar research showed that addition of Zn-Mg-Al LDHs demonstrated higher anti-oxidation effect on UV performance of AB than Mg-Al LDHs additives (53). Moreover, comparison of conventional LDHs and LDHs intercalated by sodium dodecylbenzenesulfonate, a kind of surfactants, has been conducted in terms to evaluate the effectiveness of them on the aging resistance (54). The results of this study showed that sodium dodecylbenzenesulfonate LDHs which have been prepared by anion-exchange method, have better anti-aging performance with enhanced UV aging resistance than conventional LDHs. Also, the compatibility of new LDHs with ABs was enhanced.

Additionally, to prevent or minimize the long-term oxidative aging, lignins (cross-linked 3D hydrophobic and aromatic molecules) have been used as anti-oxidants (55). Particularly, lignin is a biopolymer and it can be seen in different forms: three monolignol monomers in the form of a benzene ring with a tail of three carbons, methoxylated to various degrees and sinapyl alcohol, an organic compound structurally related to cinnamic acid (56). Due to the fact that lignins contain a large amount of phenolic groups (benzene rings with attached hydroxyl groups) their anti-oxidation effectiveness is sufficient (57). In other words, the ability of phenolic compounds to neutralize free radicals by donating either a proton or an electron makes lignin a good anti-aging candidate (58). Considering the scavenging potential of lignins on molecules of highly complex hydrocarbon systems such as ABs, was used for exploring its anti-aging capability (59). From this analysis, it was concluded that its anti-oxidation effectiveness depends on the chemical composition of lignins. The molecular structure and the performance of wood-derived lignins are dependent on the plant source, the age and moisture. Other analysis of the lignin potential performed using lignin containing ethanol co-products (60, 61). The results showed an improvement to the mechanical properties at high temperatures and a worsening to the low temperatures.

The minimization of oxidative aging using imidazoline was also evaluated (62, 63). Addition of imidazolines improves the durability of AB against oxidative aging by reducing the formation of asphaltenes during aging. Their effectiveness is dependent of chemical composition of AB and the kind of imidazolines (63). Finally, cationic additives used also as AB emulsifiers reduce the sensitivity of oxidative aging because they increase the hydrogen bonding among asphaltenes.

3.2 Rejuvenators

Rejuvenators are commonly used products capable to diffuse in and react with the aged AB and restore its adhesive and mechanical properties providing sufficient long-term performance. The rejuvenating impact of these additives depends on both the type of rejuvenator and the crude source of the binder. However, most of the results demonstrate significant variability of the properties of rejuvenated ABs and the long-term response of rejuvenated ABs, where it has been observed that aging of rejuvenated ABs is faster than the virgin binders (64).

Several rejuvenators have been developed the last years and are classified in organic and petroleum type rejuvenators. Refined tallow, waste vegetable oils, waste cooking oils, soft binder, paraffinic base oils, waste motor oils, emulsions and tertiary amines are among the different rejuvenators used.

From the previous studies in ABs it was found that usually the effectiveness and the optimum amount of rejuvenators in the aged binder is determined by conducting penetration and softening point tests or DSR analysis of rejuvenated binder. The performance of virgin AB was used as reference. Different doses of the rejuvenators are added to ABs and the visco-elastic properties are measured to obtain a target rheological performance. Experimental studies have shown that the values of stiffness and phase angle decrease and increase respectively with increasing the rejuvenator dose.

Organic type rejuvenators

Organic rejuvenators need smaller doses comparing to other rejuvenators to cause a similar rejuvenating effect on aged AB (65) and they are the most frequently referred in bibliography as vegetable oil based agents. Vegetable oils are categorized into three classes based on their sources to: (i) major oils, from human and animal-feed consumption and plants, (ii) minor oils, with fatty acid profiles and (iii) non-edible oil, plants cultivated for food production, and it has been proclaimed that their rejuvenating effectiveness is related to their asphaltene content (66). Also, about the long-term performance of rejuvenated ABs with vegetable oils, they have shown better performance than any other rejuvenator, nearly the same fatigue response as that of virgin binder (67).

Based on researches on non-edible oil rejuvenators, they are applied in industrial application for the production of soaps, paints, varnishes, resins, plastics and among them the most notable crop derived oils are Cuphea, Camelina, canola, peanut and pennycress (68). From the chemical point of view, the main molecular structure of these rejuvenators is a molecular type named triglyceride or triacylglycerol which is a structure between glycerol and fatty acids. Glycerol bonds the fatty acid molecules and their length of carbon chain results to the phase change of oil from liquid to solid (69). When these rejuvenators have longer chains of carbons their viscosity and their melting point are higher. Herein, it is important to mention that the oxidation stability of non-edible oil rejuvenators is dependent on the degree of unsaturated fatty acids in the glycerol molecules.

Waste Cooking (WC) oil is widely used to produce bio-diesel and bio-oil rejuvenator. The process of production of bio-oil is based on the esterification using alcohols and WC oil becomes fatty acid methyl ester. The new molecular structures of fatty acid methyl esters appear to include both polar (-COO-) and non-polar (-CH_2-) ends. Hydrophilic structures formed after esterification where physical properties of AB are altered resulting higher moisture sensitivity of rejuvenated AB than the aged (70). However, apart from the negative impact on the moisture performance of binder, bio-oil rejuvenates ABs, neat and SBS modified, sufficiently (71) demonstrate less tendency to short-term aging in rejuvenated ABs (72).

Similarly with WC oil, cotton seed oil contains a great amount of unsaturated fatty acids and demonstrates the same rejuvenating effect at high temperatures with other organic rejuvenators. Pongamia oil as product of the seeds of plant pongamia pinnata and a mix of castor oil with coke oven gas condensate have been investigated as alternative organic rejuvenators (73). Chemical analysis of pongamia oil showed high amounts of oleic and linoleic acids which make the rejuvenator to behave as a non-polar oil. Additionally, the analysis of chemical substances of mix oil with 30% of coke oven gas condensate and 70% of castor oil by weight of the total mix demonstrated high amounts of ricinoleic acid (polar molecules) and napthenic aromatics from coke and castor oil, respectively. The high polarity of ricinoleic acids within the coke gas condensate is the main reason of dissolution of asphaltene in aged AB. Using the same dose of both oils, the rejuvenated AB displayed desirable rutting and fatigue behaviors even better than the virgin AB. However, another research showed that organic type rejuvenators based on oleic acids appeared the lowest capacity to restore aged AB at high temperatures comparing the petroleum type rejuvenators (74).

Bio-binder rejuvenator formed from swine manure was designed and its effect on aged ABs was evaluated conducting mechanical analysis at low temperatures (70). Ductility and fracture energy of aged ABs were improved by adding these, resulting also in improvement of rheological properties. Apart from the improvement at low-temperature properties, the high temperature rutting resistance of manure-based rejuvenator has been proved as well. Chemo-rheological studies conducted using bio-binders from spirulina algae (micro-algae), swine manure, and nano-algae from others (75). Bio-binders were blended with a conventional AB and the rejuvenating effect was demonstrated estimating also the durability enhancement of AB at low temperature conditions. Similar study on the synthesis of microalgae rejuvenators showed that, when proteins are removed, lipid fractions remained (76). Free fatty acids were the main soluble components (methyl esters, palmitic acid, stearic acid, oleic acid, linoleic acid and linolenic acid) of lipid fractions of microalgae and the application of those rejuvenators can be feasible. Apart from the improvement of anti-oxidation potential, the waste coffee grounds or ground dry coffee beans have displayed increased resistance in short and long-term aging (76). Moreover, the utilization of fractionated bio-oil with biomass from different sources (oak wood, switchgrass and corn stover) demonstrated considerable benefits for ABs (77).

Petroleum type rejuvenators

Refining and modification of light and heavy crude oil is the major source of petroleum type rejuvenators. These rejuvenators are mainly aromatic, napthenic and paraffinic oils with varying molecular weights. The arrangement of bonds of carbons and hydrogens results to different molecular structures and subsequently determine whether the rejuvenator is aromatic, napthenic or paraffinic (69).

Aromatic extract is a traditional rejuvenator with dominant polar aromatic molecules. The aromatics can be processed by either the paraffinic or napthenic production processes and they are separated out with solvent extraction processing or cracking into smaller molecules during hydro-treating. Paraffinic type rejuvenators consist of straight or branched chains of hydrogen and carbon atoms containing at least 18% of aromatics (78). The third most widely used petroleum type of rejuvenators is napthenic which can be viewed either in a simple or complex ring structures of molecules with high content of aromatics, approximately 44% (78).

In many cases, petroleum type rejuvenators can be found as a mix of aromatic oil and resin compounds with small concentrations of saturates. When aromatic extract is used as rejuvenator, it was evaluated that temperature plays a crucial role for reaching a high rejuvenation rate for different types of ABs (79). According to the same study on the rejuvenation effect of aromatic extract, it was found that the recovery of rheological properties of aged ABs by applying aromatics was in a lower extent than VW oil with same proportion of added agent.

However, from another study it was found out that rejuvenators formed from paraffinic oils were the most capable of rejuvenating aged ABs at high and low temperatures while rejuvenators obtained from aromatic extracts were the least at low temperatures (74). From the same study, the fatigue resistance was improved using petroleum rejuvenators without substantially influencing rutting performance.

Finally, an example for engineering petroleum produced rejuvenators is the dodecenyl succinic anhydride which consists of tetrapropenyl moieties (mono unsaturated branched hydrocarbons) and succinic anhydride groups (80). Also, the rejuvenating ability of emulsion type additives is well known in which emulsion rejuvenators can affect the change in stiffness of the aged AB sufficiently (81, 82). However, a comparative study showed that the restoring impact of these, such as the polymerized maltene-based emulsion composed of petroleum resin oil base, is lower than organic rejuvenators (83) or even the same (84).

4. CONCLUSIONS

Chemistry of aging mechanisms and key parameters of aging of ABs have been discussed in this study. An overview of the current-state-of-the-art of anti-aging technologies of AB has also been reviewed providing the latest bibliography. Based on this bibliography it is evident that identification of chemical reactions of AB during hardening due to aging can assist to design and improve binders producing last longer asphalt pavements. Using the gained knowledge of the exact mechanism of oxidation and anti-oxidation of AB can enhance the applications of anti-aging technologies as well.

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