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THE ROLE OF BIO-BASED ADDITIVES IN ACHIEVING SUSTAINABILITY IN ASPHALT PAVEMENTS

ROLA DODATKÓW NA BAZIE BIOLOGICZNEJ W OSIĄGANIU ZRÓWNOWAŻONEGO ROZWOJU NAWIERZCHNI ASFALTOWYCH

STRESZCZENIE. Zwiększone zapotrzebowanie na usługi związane z nawierzchniami asfaltowymi ze względu na stale rosnące natężenie ruchu, w połączeniu ze starzeniem się sieci autostrad i wezwaniami do poprawy zrównoważonego rozwoju w całej branży, sprawiły, że potrzeba inteligentnych i zrównoważonych materiałów i konstrukcji nawierzchni stała się ważniejsza niż kiedykolwiek wcześniej. Podczas gdy chemiczne dodatki do mieszanek wykonanych w technologii na ciepło i technologie odświeżające były wykorzystywane w materiałach nawierzchniowych na różną skalę w badaniach i praktyce w przeszłości, w ostatnich latach dodatki na bazie biologicznej pojawiają się jako coraz bardziej praktyczne rozwiązania dla potencjalnie bardziej zrównoważonych nawierzchni, oferując perspektywę wysokiej wydajności w połączeniu z równowagą środowiskową i ekonomiczną. Dostosowanie chemicznych dodatków do mieszanek wykonanych w technologii na ciepło i środków odświeżających w praktyce wymaga praktycznej wiedzy na temat definicji, odpowiednich kryteriów oceny dostępnych dla praktyka i, co być może najważniejsze, udokumentowanego doświadczenia w zakresie skutecznego stosowania w praktyce. W niniejszym opracowaniu dokonano przeglądu bieżących wysiłków podejmowanych w branży w celu włączenia bio-chemicznych dodatków do mieszanek wykonywanych w technologii na ciepło i środków odświeżających do metod projektowania opartych na wydajności dla HMA i WMA, przy użyciu rzeczywistego projektu zrównoważonej mieszanki (BMD). Przykłady, w tym kompleksowe badania prowadzone w połączeniu z NCAT i MnROAD, przeanalizowano w celu zilustrowania wykorzystania takich koncepcji w praktyce.

SŁOWA KLUCZOWE: rejuwenator, mieszanka na ciepło, recykling, zrównoważony asfalt.

ABSTRACT. Increased service demands from asphalt pavements due to ever-increasing volumes, coupled with the aging of highway networks, and calls for improved sustainability across the industry, have rendered the need for smart and sustainable pavement material and design more important than ever. While chemical warm mix additives and rejuvenating technologies have been utilized in pavement materials at various scales of research and practice in the past, in recent years bio-based additives have emerged as increasingly practical solutions for potentially achieving more sustainable pavements, offering the prospect for high performance combined with environmental and economic sustainability. Adaptation of chemical warm mix additives and rejuvenators in practice requires a working knowledge on the definitions, relevant evaluation criteria available to the practitioner, and, perhaps most importantly, demonstrated experience of successful application in practice. The present study will review current efforts underway in the industry to incorporate bio-based chemical warm mix additives and rejuvenators in performance-based design methods for HMA and WMA, using real world Balanced Mix design (BMD). Examples including comprehensive research being carried out in conjunction with NCAT and MnROAD research and test facilities will be reviewed to illustrate the utilization of such concepts in practice today.

KEYWORDS: rejuvenators, warm mix, recycling, sustainable asphalt, field performance.

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1. INTRODUCTION

Warm mix additives (WMA) have been in use through multiple forms and processes since the early use in Europe in the 1990s [1]. Additives have commonly played a role in warm mix asphalt in later years, often broadly categorized as “organic additives” and “chemical additives”. Common examples of organic additives are Fischer-Tropsch and Fatty Amid waxes [2, 3]. These materials have melting points that are lower than typical hot mix asphalt compaction temperatures, acting as bitumen plasticizers (viscosity reducers) when above their melting temperatures, and as bitumen stiffeners when below their melting point. The plasticization process has been observed to help with compaction, however its significant impact on bitumen standard grades has required the industry to adopt suitable specifications around the impact of such additives.

Chemical warm mix additives have been used successfully for years across the world. Their use has become especially prevalent in North America and parts of Europe due to the ease of implementation and lack of impact on standard bitumen grade. Such additives are believed to perform through improving the ability of the bitumen to coat the aggregates, rather than reduction of viscosity [2]. Some research on this topic has suggested modification of bitumen surface free energy [4] and the internal friction [2] as driving forces of improving mixture densification, without significant change in bitumen rheological properties and standard grade.

Rejuvenators, also known as recycling agents, are a more recent addition to the asphalt industry’s toolbox of additives. Many additives have been investigated as potential recycling agents, often utilizing different types of categorization methods based on the source or manufacturing process [5, 6, 7, 8]. Furthermore, researchers have increasingly employed terms such as “Rejuvenation” vs. “Softening" in recent years. Tabatabaee and Kurth proposed a functional categorization of recycling agents based on the bitumen fraction most affected by the additive and the expected mechanism of effect upon addition to aged bitumen, based on which the following categories were proposed [9, 10, 11]:

- “Soluble Softener” which supplements the “solvent” phase of the bitumen colloidal structure by being most compatible with the low polarity naphthenic aromatic fraction of the bitumen. Such additives reduce the viscosity and modulus of the overall bitumen through lowering the viscosity of the continuous solvent phase, but may have little effect on the intermolecular agglomeration and self-assembly of the polar micelles.
- “Compatibilizers” which have affinity for multiple fractions in the bitumen and may be derived through careful engineering of the source material, whether petroleum- or bio-based. In addition to reduction in viscosity, these additives are hypothesized to result in a reduction in high molecular weight micelle agglomerations through disruption of the intermolecular associations and molecular self-assembly, similar to the postulated effect of the bitumen “resin” phase.
- “(Phase-) Incompatible Softeners” which often exhibit low compatibility with the low polarity naphthenic aromatic and polar fractions, especially at lower temperatures. This category may include some paraffinic and saturated material with high crystalline fractions. It was speculated that although dispersion of such lower viscosity additives in the bitumen may still achieve a reduction in overall bitumen modulus, increasing the dosages of “insoluble softeners” in bitumen may lead to colloidal instability and the long term durability and phase stability may be compromised [9, 12].

Although precise method of specifying warm mix additives vary from region to region, an overall consensus on approach seems to have emerged over the last decade of use in North America. The agency will generally approve an additive for use in mix designs based on a combination of prior history of use, and laboratory data. This usually consists of the following steps:

A. The laboratory binder tests will typically consist of confirming that the standard performance grade (Penetration / softening point grade) can be maintained at typical dosages. This does not mean that zero impact is observed, but only that the grade can be reliably maintained.

B. At the mixture scale, the rutting and/or moisture resistance performance of the WMA mix is checked against typical mix requirements for a reference mix design and material. This is typically achieved by ITSR (indirect tensile strength ratio) testing, or the Hamburg wheeltracking test.

However, less precedent exists with regards to specifying the use of rejuvenators. A number of states and municipalities have started adopting performance-based specifications as means for approving higher recycled content mixes, including the potential use of rejuvenators. Newly updated standard documents such as the ASTM D4552-20 also provide a general baseline for classifying recycling agents that are safe and suitable for use in the asphalt plants and production and is being considered for inclusion in high RAP specifications.

2. MATERIAL AND DESIGN

Table 1 shows a summary of the mix types used in the various demonstration projects in this study. For the NCAT sections the aggregate and RAP were sourced from the State of Virginia, while a local source of PG64-22 binder was used. The material used for the MnROAD sections, including the virgin binder, were sourced from Minnesota. Table 2 provided a generic description of the additives used in the project.

The NCAT sections were produced using the provisional Balanced Mix Design proposed at that time by Virginia Department of Transportation (VDOT). The VDOT performance criteria are shown in Table 3. The MNROAD sections were designed by comparison of the Disc Compact Tension (DCT) and Hamburg Wheel Tracking performance between the high RAP and control test sections as shown in Table 4.

Table 5 shows the aggregate gradations, and volumetric properties for the NCAT and MNROAD sections at the various RAP contents. The binder content from quality control testing in the field is also included, where available.

Table 1. Bitumen Properties

Mix Designations	RAP (%Wt. Mix)	PG Binder	Additive
NCAT 9.5mm 30%RAP WMA	30	PG64-22	Anova 1501/1503
NCAT 9.5mm 45%RAP Rejuvenated	45	PG64-22	Anova 1815/1817
NCAT 9.5mm 45%RAP No Rejuvenator	45	PG64-22	Anova 1501/1503
MnROAD 12.5mm 25%RAP	25	PG58-28	None
MnROAD 12.5mm 45%RAP Rejuvenator	45	PG58-28	Anova 1815/1817

Table 2. Material Matrix

Type	Name	Description
Chemical Warm Mix	Anova® 1501/1503	A bio-based non-hazardous liquid warm mix additive, design for impact at low dosage without changing the bitumen grade
Recycling Agent	Anova® 1815/1817	An engineered bio-based oil, based chemical modification of vegetable oil for bitumen compatibility and oxidative stability

Table 3. VDOT Provisional Balanced Mix Design Criteria [13]

Test	Procedure	Criteria
Asphalt Pavement Analyzer (APA) rutting	Testing is conducted to 8,000 cycles at 64°C with a wheel load of 120 lb and a rubber hose pressure of 120 psi. Sample consists of two 150mm diameter cylindrical compacted pills at 7 ± 0.5%	Rutting depth ≤8.0mm
Indirect Tension Asphalt Cracking Test (IDEAL-CT)	150 mm diameter specimens are conditioned at 25 ± 1°C for 2 ± 0.5 hours. Loading is applied using load-line displacement control at 50 mm/minute	CTindex ≥70; CT-Index is calculated based on the area under the curve and the post-peak slope
Cantabro Abrasion Test	Testing is conducted to 300 rotations at a speed of 30-33 rotations per minute. Test conducted on 150 mm cylindrical samples compacted at prescribed design gyrations	Mass loss ≤7.5%

Table 4. Criteria used for performance design approval of MNROAD mix designs

Test	Procedure	Criteria
Hamburg Wheel Tracking (HWT)	Tested at 45°C following AASHTO T324 on 150mm diameter cylindrical compacted pills at 7±0.5%	Passes to rut depth of 12.5 mm higher than Control mix
Disc Shaped Compact Tension Test at -20°C	ASTM D7313-13 MnDOT Modified	Fracture energy ≥450 J/m^2

Table 5. Design and Construction for the Pavement Sections

Sieve Size/ %wt. Passing	NCAT Sections		MNROAD Sections	
	30%RAP	45%RAP	25% RAP	45%RAP
1"	100	100	100	100
3/4"	100	100	100	100
1/2"	100	100	91.1	92.4
3/8"	97	97	81.7	84.6
#4	61	61	60.5	69
#8	38	38	48.7	57.2
#16	27	28	35.8	43
#30	20	21	24.1	29
#50	14	15	13.8	16
#100	10	10	7	7.8
#200	5.5	6.3	4.1	4.7
Design Binder Content	5.5	5.8	5.1	5.1
QC Binder Content	6	6	N/A	5
Dust to Binder Ratio	1.1	1.1	0.83	1.0
RAP Binder Replacement	25%	38%	20%	31%
Design Air Voids	2.9	2.3	3.8	4.0
VMA	17.3	16.3	15.1	15.0
VFA	85	91	74.8	73.2

3. RESULTS AND DISCUSSION

3.1. WARM MIX ADDITIVE TEST SECTION, NCAT

Chemical warm mix additives have many years of proven field performance. A good example of monitored use of chemical warm mix additives in pavements is that of the test section constructed in 2018 at the National Center for Asphalt Technology (NCAT) test track in Auburn, USA. The test section used 0.5% of Anova® chemical warm mix additive (by weight of total binder) and as of April of 2021 has been subjected to 10 million equivalent single axle loads (ESALs) applied by truck traffic. This level of traffic is beyond that experienced by most pavements and presents a robust assessment of the performance of such materials. The field performance, as shown in Fig. 1.

The plant produced material was subjected to thorough mixture performance testing in parallel to the continuous weekly pavement condition assessment. Comparing the results shown in Table 6 with the corresponding typical HMA performance thresholds confirms that mixes uses chemical WMA can perform at the same level as that of a typical HMA.

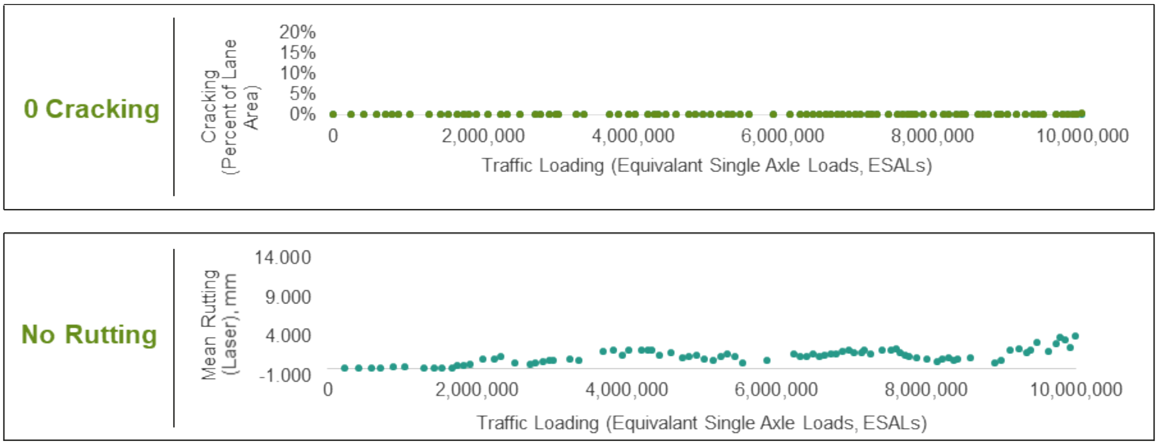

Fig. 1. Field performance from monitored NCAT test section after 10 million ESALs of loading [13]

Table 6. Mixture performance results from NCAT test section

Distress Type	Test Name and Method	Test Temperature	Unit	**WMA Test Result**	Typical Threshold
Thermal Cracking	Disc Compact Tension (DCT) -12°C ASTM D7313 (MNDOT)	-12°C	J/m^2 Standard Deviation	**529** **59**	450 (min)
Cracking	IDEAL-CT ASTM D8225	25°C	CT_{Index} (-) Standard Deviation	**102** **15**	70 (min)
Cracking	Overlay Tester NJDOT B-10	25°C	Cycles to Failure Standard Deviation	**296** **70**	200 (min)
Rutting	Hamburg Wheeltracking Test AASHTO T-324	50°C	mm at 10K Cycles	**2.5**	12.5 (Max)
	Hamburg Wheeltracking Test AASHTO T-324	50°C	mm at 20K Cycles	**3.2**	12.5 (Max)
Rutting	Asphalt Pavement Analyzer AASHTO T-340	64°C	mm Standard Deviation	**2.97** **0.48**	8 (max)

3.2. HIGH RAP REJUVENATED TEST SECTION, NCAT

The high RAP test section was constructed adjacent to the section containing the Anova warm mix additive. Two mixes were produced using 45% RAP content, with one containing the Anova rejuvenator and placed on the field section, while subset of the production at 45% RAP contained no rejuvenator. The latter mix was not placed on the field but was sampled for lab testing and comparison, results of which are shown in Table 7 [13].

Figure 2 shows the field performance of the high RAP rejuvenated test section after being subjected to 10 million equivalent single axle loads (ESALs) applied by truck traffic. The mix performance comparison in Table 7 shows that the use of the rejuvenator resulted in a significant improvement in cracking resistance as measured by multiple test methods. The results are a demonstration of the ability of performance testing to capture the impact of such additives.

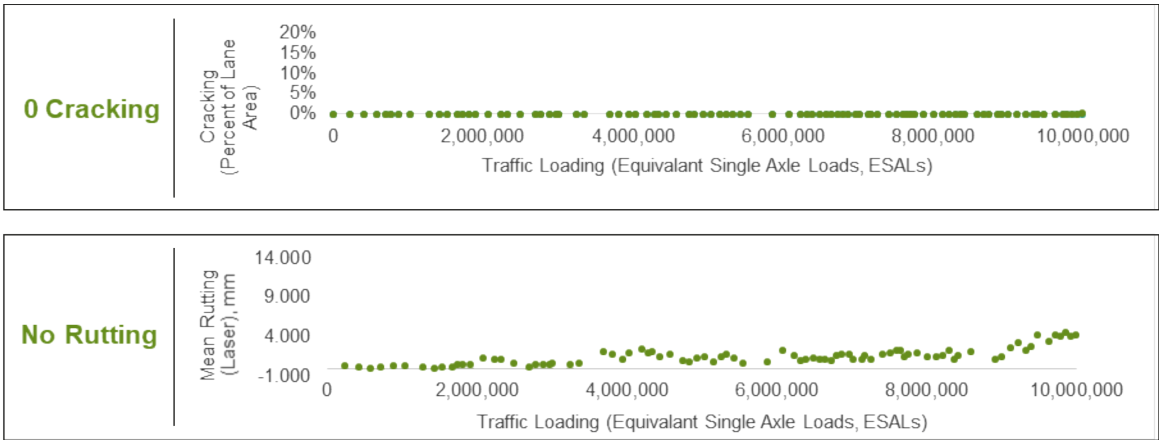

Fig. 2. Field performance from monitored NCAT high RAP test section after 10 million ESALs of loading [13]

Table 7. Mixture performance results from NCAT High RAP test section

Distress Type	Test Name and Method	Test Temperature	Unit	**High RAP + Rejuvenator**	**High RAP**
Cracking	IFIT Flexibility Index	25°C	(–)	8	3.7
	Standard Deviation		Standard Deviation	2.3	1.2
Cracking	IDEAL-CT	25°C	CT Index (–)	64	45
	ASTM D8225		Standard Deviation	12	9
Cracking	Overlay Tester	25°C	Cycles	325	72
	NJDOT B-10		Standard Deviation	2.51	1.86
Thermal Cracking	Disc Compact Tension (DCT) -12°C	-12°C	J/m²	562	494
	ASTM D7313 (MNDOT)		Standard Deviation	48	57
Rutting	Hamburg Wheeltracking Test	50°C	mm at 10K Cycles	2.6	
	AASHTO T-324				
	Hamburg Wheeltracking Test	50°C	mm at 20K Cycles	3.1	
	AASHTO T-324				
Rutting	Asphalt Pavement Analyzer	64°C	mm	3.4	
	AASHTO T-340		Standard Deviation	0.87	

3.3. HIGH RAP REJUVENATED TEST SECTION, MNROAD

Two sections were built on Interstate 94 at the Minnesota Road Research Facility (MnROAD) in Monticello, MN. Sections were built at either end of MnROAD, as shown below. The control mix met MnDOT requirements for the location and traffic volume demands. The RAP content was increased from 25% in the control mix to 45% for the Anova® mix. The high RAP was rejuvenated to offset the impacts of increasing the reclaimed asphalt pavement (RAP) content.

Table 8 shows a comparison of the performance of the two produced mixes. The design objective was to achieve similar performance between the higher RAP mix with Rejuvenator, and that of the standard lower RAP mix. The mix performance results are statistically similar in all cases except potentially for the overlay tester and the Hamburg wheel-tracking results, for both which of the

Table 8. Mixture performance results from MNROAD High RAP test section

Distress Type	Test Name	Temperature	Unit	25% RAP Control	45% RAP + Rejuvenator
Thermal Cracking	Disc Compact Tension (DCT) -20°C ASTM D7313 (MNDOT)	-20°C	J/m^2 Standard Deviation	468 (28.2)	458 (62)
Rutting	Hamburg Wheeltracking Test AASHTO T-324	50°C	mm at 5K Cycles	7.1	2.3
Cracking	IDEAL-CT ASTM D8225	25°C	CTIndex (-) Standard Deviation	55.5 (4.5)	66.9 (12.6)
Cracking	Overlay Tester NJDOT B-10	25°C	Cycles Standard Deviation	239 (9.7)	449 (158.4)
Thermal Cracking	Disc Compact Tension (DCT) -12°C ASTM D7313 (MNDOT)	-12°C	J/m^2 Standard Deviation	618 (132.6)	595 (150.9)
Cracking	IFIT Flexibility Index Standard Deviation	25°C	(-) Standard Deviation	9.2 (2.35)	8.7 (2.67)

rejuvenated mix seems to outperform the control. By all measures, the performance of both mixes is satisfactory.

A portion of each section that had comparable structural thickness and traffic pattern was identified for long-term field performance monitoring. Due to the location in the MnROAD transition area, all performance data needed to be collected under live traffic, which eliminates many of the MnROAD field performance monitoring tools. MnDOT regularly collected data over the entire project length sections using a Pathways Services Inc. high-speed, digital inspection vehicle. The average International Roughness Index (IRI) and the average rut depth were measured in both left and right wheel paths; the data reported in this document were averaged for both wheel paths in both lanes. The roughness index has shown no significant increase for any of the test sections.

As expected with asphalt mill and inlay projects in Minnesota, reflective cracking has been observed in the sections. Reflective cracking was apparent at the project extents where only a single 2” lift of asphalt was placed over concrete pavement. It is important to point out that no difference in cracking has been observed in the Anova® sections and that the mill and inlay sections were expected to develop reflective cracking. The MnROAD research team is currently working to quantify the percentage of cracking for each section. Overall, to date, the rejuvenated test sections appear to show good performance similar to the control sections.

4. CONCLUSIONS

This paper briefly reviewed the typical impact, process, and specifying practice for use of biobased chemical warm mix additives and a biobased rejuvenator for making high performance mixes with potentially improved sustainability aspects. Such additives have been shown to be robust and reliable methods of achieving pavement density at reduced temperatures or increased haul distances, without the complication of potential change in bitumen standard grade.

The typical test methods shown in the presented projects may be considered as examples of how a performance-based specification process might look like and provide some points of consideration for agencies looking to reliably and efficiently incorporate such technologies in their districts.

REFERENCES

[1] *Bonaquist R.*: NCHRP Report 691: Mix Design Practice for Warm Mix Asphalt. National Cooperative Highway Research Program, Washington D.C., 2011

[2] *Caputo P., Abe A.A., Loise V., Porto M., Calandra P., Angelico R., Rossi C.O.*: The Role of Additives in Warm Mix Asphalt Technology: An Insight into Their Mechanisms of Improving an Emerging Technology. Nanomaterials, **10**, 6, 1202, 2020, DOI: 10.3390/nano10061202

[3] *Kheradmand B., Law T.H., Muniandy R., Yunus R.*: An overview of the emerging warm mix asphalt technology. International Journal of Pavement Engineering, **15**, 1, 2014, DOI: 10.1080/10298436.2013.839791

[4] *Kakar M.R., Hamzah M.O., Akhtar M.N., Woodward D.*: Surface free energy and moisture susceptibility evaluation of asphalt binders modified with surfactant-based chemical additive. Journal of Cleaner Production, **112**, 4, 2016, 2342–2353, DOI: 10.1016/j.jclepro.2015.10.101

[5] *Lei Z., Golalipour A., Tabatabaee H., Bahia H.*: Prediction of Effect of Bio-Based and Refined Waste Oil Modifiers on Rheological Properties of Asphalt Binders. Transportation Research Board 93rd Annual Meeting Compendium of Papers, Washington D.C., 2014

[6] *Hill B., Oldham D., Behnia B., Fini E., Buttlar W., Reis H.*: Low Temperature Performance Characterization of Bio-Modified Asphalt Mixtures Containing Reclaimed Asphalt Pavement. Transportation Research Record: Journal of the Transportation Research Board, **2371**, 1, 2013, 49–57, DOI: 10.3141/2371-06

[7] *Nahar S.N., Qiu J., Schmets A.J.M., Schlangen E., Shirazi M., Van De Ven M.F.C., Schitter G., Scarpas A.*: Turning Back Time: Rheological and Microstructural Assessment of Rejuvenated Bitumen. Transportation Research Record: Journal of the Transportation Research Board, **2444**, 1, 2014, DOI: 10.3141/2444-06

[8] *Zaumanis M., Mallick R.B., Poulikakos L., Frank R.*: Influence of six rejuvenators on the performance properties of Reclaimed Asphalt Pavement (RAP) binder and 100% recycled asphalt mixtures. Construction and Building Materials, **71**, 2014, 538–550, DOI: 10.1016/j.conbuildmat.2014.08.073

[9] *Tabatabaee H., Kurth T.*: Analytcial Investigation of the Impact of a Novel Bio-based Recycling Agent on the Colloidal Stability of Aged Bitumen. Journal of Road Materials and Pavement Design, **18**, Sup2: EATA 2017, 2017, 131–140, DOI: 10.1080/14680629.2017.1304257

[10] *Tabatabaee H., Kurth T.*: Rejuvenation vs. Softening: Reversal of the Impact of Aging on Asphalt Thermo-Rheological and Damage Resistance Properties. Proceedings of the International Society for Asphalt Pavers (ISAP), Jackson, WY, USA, 2016

[11] *Tabatabaee H., Kurth T.*: Critical Comparison of Asphalt Recycling Agents From Bio-based and Petroleum Sources. Proceedings of the 22 Encandro de Asfalto (IBP), Rio de Janeiro, Brazil, 2016

[12] *Johnson K.-A.N., Hesp S.A.M.*: Effect of Waste Engine oil Residue on Quality and Durability of SHRP Materials Reference Library Binders. Transportation Research Record: Journal of the Transportation Research Board, **2444**, 1, 2014, DOI: 10.3141/2444-12

[13] *West R., Timm D., Powell B., Tran N., Yin F., Bowers B., Rodezno C., Leiva F., Vargas A., Gu F., Moraes R., Nakhaei M.*: NCAT Report 21–03 – Phase VII (2018-2021) NCAT Test Track Findings, National Center for Asphalt Technology, 2021