International Journal of GEOMATE, May, 2018 Vol.14, Issue 45, pp.116-123
Geotec., Const. Mat. & Env., DOI: https://doi.org/10.21660/2018.45.7328
ISSN: 2186-2982 (Print), 2186-2990 (Online), Japan

INVESTIGATION OF RUTTING PERFORMANCE OF DIFFERENT WARM MIX ASPHALT (WMA) MIXTURES

*Ivan Syed[1], Md Amanul Hasan[2] and Rafiqul A. Tarefder[3]

[1]Graduate Research Assistant, University of New Mexico, United States; [2]PhD Student, University of New Mexico, United States; [3]Professor, University of New Mexico, United States

*Corresponding Author, Received: 17 May 2017, Revised: 07 Aug 2017, Accepted: 12 Sept 2017

ABSTRACT: Use of warm mix asphalt (WMA) in pavement industries has been growing rapidly over last decade because it can lower down the construction temperature and subsequently reduces the environment pollution and energy consumption. There are mainly two different types of WMA technology are available: water-based foaming, and chemical additives. One of the challenges to WMA technology, the uncertainty about performance of WMA mixtures is still unclear. To this end, this study investigated the rutting performance (one of the major distresses) of mixtures with different WMA additives. Rutting performance of WMA mixtures with four different additives (Terex® foaming, Evotherm®, Cecabase®, and Cecabase®+) were evaluated and compared with the control (un-modified) hot mix asphalt (HMA) mixture through Hamburg wheel track test (HWTT). Results showed that all WMA mixtures have lower rut depth compared to control HMA mixture. It is also observed that Terex® and Cecabase® samples exhibited better rutting resistance than Evotherm® sample. However, Cecabase®+ WMA sample showed significant enhancement in rutting resistance due to presence of polymer. In addition to mixture test, extracted binders from these mixtures were also evaluated though Superpave performance grade (PG) and multiple stress creep recovery tests. The performance orders of the extracted binders from these two tests are also similar as the mixture performance. This study also found that non-recoverable compliance (J_{nr}) value obtained from the MSCR test demonstrated better correlation with HWTT ($R^2 = 0.96$) compared to Superpave rutting parameter ($R^2 = 0.68$).

Keywords: Warm mix additives, Rutting resistance, PG temperature sweep, MSCR

1. INTRODUCTION

Global concerns over the gradual depletion of non-renewable natural resources and increasing damage to the ecosystem from greenhouse gas emissions, generated from human productivity, have created greater awareness within the past two decades for sustainable development practices in all spheres of human endeavor including the pavement construction industry. Within the construction industry, construction and maintenance processes involved with pavement are known to be resource-intensive, sometimes with considerable negative environmental impacts. This places elevated responsibility on industry professionals, to indulge in sustainable construction practices, in order to ensure that the activities of today's generation would not compromise and be detrimental to the ability of tomorrow's generation to prosper unhinged. It is reported that in the United States (U.S) alone, over 320 million tons or raw materials are used in the construction, rehabilitation and maintenance operations of the nation's road infrastructure network; project annual costs of over $150 billion [1].

In perspective of global use, the associated costs for the volume of raw materials used and energy consumption required for asphalt production cost could be astounding. The increasing costs of raw materials and demand for environmentally suitable paving materials in road construction have challenged the asphalt industry to seek and develop alternatives that aid in reduction of production and compaction temperatures of asphalt mixtures without compromising the required performance behavior.

Warm mix asphalt (WMA), pioneered in Europe in the late 1990's [2], is the latest asphalt technology that presents the capability of addressing the practice of environmental sustainability and enhancement of mixture workability without compromising performance. WMA additives can reduce the viscosity of the binder, allowing mixtures to be produced at a temperature grade of 38°C lower than traditional Hot mix asphalt (HMA) [3], [4], which lead to a number of environmental, operational, and economical benefits.

The implementation of WMA has become more widespread with an increasing number of paving contractors employing these sustainable technologies in construction in order to take advantage of reduced mixing and compaction temperatures, lowered energy usage for production and placement, and reduced emissions. However, one of the challenges to implementation is the uncertainty about how WMA may affect asphalt

mixtures' short and long-term field performance. Research has shown that as mixing temperature are reduced for WMA, the mixes show increased tendencies towards rutting and moisture susceptibility [5], [6]. This was attributed to decreased aging of the binder, possible presence of moisture in the mixture incomplete drying of the aggregates due to lower temperatures.

A better understanding of the effects of warm mix additives on the performance of asphalt concrete is a fundamental step towards the effective application of WMA. As part of the structural design processes to optimize field performance of asphalt mixtures, simple performance tests such as Hamburg Wheel Tracking Test (HWTT) has been developed to determine rutting potential. However, the characteristics of the binder component are also important, especially for cases involving binders with modifying agents.

Despite the fact that asphalt bitumen make up 4 to 8 % of a pavement mix structure, it provides a level of rigidity, structural bonding, resilience, and absorbance which holds the total pavement mixture together as a solid body [7]. However, with higher traffic densities and effects of environmental exposure, binder flows and dissipates energy with time [8]. As a result, asphalt binder experience a variety of thermomechanical demands; where pavement defects transpire such as rutting at high temperatures due to thermal susceptibility of asphalt [9].

The asphalt contribution to permanent deformation process has traditionally been handled by observing the asphalt binder's consistency based on softening point and penetration tests [10] . However, with priorities set for environmental conservation and preservation, the integration of polymer modifiers, warm mix additives, and recycling of reclaimed asphalt pavement (RAP) materials into asphalt mixtures have gained popularity [11], [12]. With this in mind, the empirical tests mentioned earlier are insufficient to characterize the rutting resistance behavior of binders. It would be helpful to examine the effects of these modifying agents on the properties of plant produced mixtures. In order to accomplish this task, extraction and recovery of asphalt binder from asphalt concrete were performed.

Thus, this research evaluates the rutting resistance of binders modified with different warm mix additives.

2. OBJECTIVES

I. Evaluate the effects of different warm mix additives on the rutting performance asphalt concrete.
II. Investigate the rutting potential of extracted binders from the WMA mixtures.
III. Assess the correlation between binder properties and mixture rut depth.

3. TEST METHODOLOGY

This section of the paper focuses on material selection, experimental plan, and a brief description of each test considered for the purpose of this research. The test methodology is described in Fig.1, where this test program is designed to evaluate the rutting susceptibility of the selected pavements and to see if there are demonstrable differences in test results between control HMA and WMA modified test sections. This study was conducted in two phases: 1) rutting performance evaluation and 2) assessment of extracted binder properties. The rutting potential of WMA modified asphalt mixtures, in comparison to HMA, were evaluated through HWTT device. As samples were collected from the LTPP pavement sections, binders on these plant-produced asphalt mixtures experienced short-term aging during their production stage [13]. The process of laboratory short-term aging was annulled. Both conventional Superpave Performance Grade (PG) and new Multiple Stress Creep Recovery (MSCR) tests were conducted to evaluate the rutting susceptibility of the binder. These rheological tests were performed using a Dynamic Shear Rheometer (using a 25 mm diameter plate and 1 mm gap). The average values of three replicates samples were determined at 50°C, corresponding to the test temperature of the HWTT test.

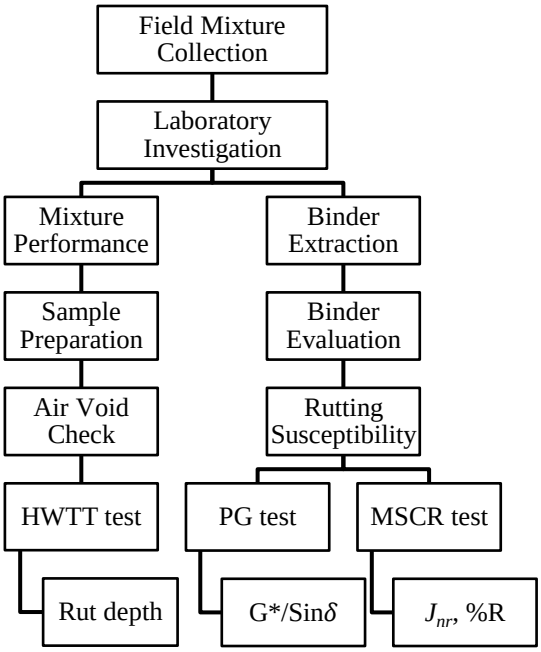


Fig.1 Experimental plan adopted in this study

3.1 Material Source and Classification

The pavement test sections selected for this research are located in district four of central New Mexico and were constructed in fall of 2014 along the westbound lane of Interstate 40 near Santa Rosa, New Mexico, where designs incorporate approximately 20% RAP materials collected from the Interstate 40 and US 84 highway stockpile.

Table 1 Locations of pavement test sections [14]

SHRP ID	Design Factor	Latitude	Longitude
35AA01	Control	34.9887	-105.2338
35AA02	Foaming	34.9889	-105.2379
35AA03	Evotherm®	34.9893	-105.2459
35AA61	Cecabase®	34.9909	-105.2789
35AA62	Cecabase®+	34.9911	-105.2839

Note: All aggregates meet SP-III gradation and all mixtures contain 1% versabind®. Cecabase®+ mixture contains polymer modified binder.

Material type of sand and gravel with gradation classification of Superpave Mix type III with nominal maximum aggregate size (NMAS) of ¾ inches were utilized for design of these AC mixes (as shown in Fig.2). In addition, 1% of versabind® were incorporated into the mixes.

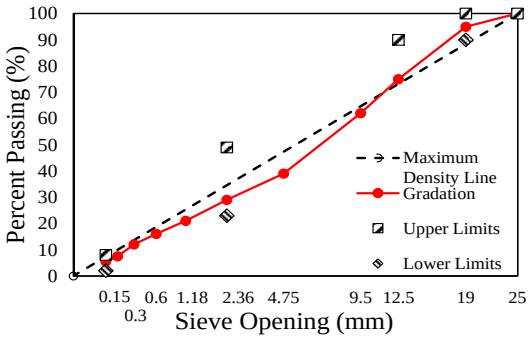


Fig.2 Gradation curves of evaluated AC mixtures

The production of asphalt concrete utilized in the second test section were produced with Terex® Foaming technology and WMA chemical additive of Evotherm® was used in the construction of the third test section. Cecabase® chemical additives was considered for the two supplemental pavement test sections in order to perform additional research on the effects of other WMA production methods. The asphalt concrete mixing temperature considered for design of HMA and WMA were 322°F and 270°F, respectively. The first four pavement sections were manufactured using binder grade of PG 70-28. However, the last section was prepared with the same binder grade and enhancement of polymer modifiers, thus resulting in the designation of PG 70-28+.

Based on the different additives used in these test sections, WMA technology is classified into two different technologies namely: (i) water-based and (ii) chemical additive technologies. In the foaming process, a certain amount of water is added to the hot binder and then the water is turned into steam, which results in a volume expansion of binder and consequently, a reduction of the binder's viscosity [15]. This temporary reduction facilitates aggregate coating and thereby improved workability at reduced temperatures. The expanded volume gradually deteriorates with time and the asphalt binder returns to its original characteristics [16]. This form of technology is currently more popular and widely used compared to other technology categories.

Evotherm® and Cecabase®, for instance, are both chemical additives. Cecabase® which do not reduce the asphalt binder's viscosity. They are packaged by surfactant and adhesion agents, which chemically enhance active adhesion and improve the wetting of aggregates by binder without altering considerably the rheological performance [6]. Evotherm® is an additive packaged in the form of emulsion, which are introduced into the plant's binder line, allowing for the reduction of mixing temperatures close to 38°C, translating to decreased energy requirements for asphalt production [17].

3.2 Mix Performance Evaluation Tests

Mixture rutting performance was done using HWTT following AASHTO T 324-14, a laboratory test procedure which simulates repeated wheel loading on specimens in order to characterize rutting resistance potential and stripping susceptibility. Linear variable displacement transducers (LVDTs) located at the side of each wheel are used to record the rut depth at 11 points along the test samples with 0.01 mm precision. Following the recommendation suggested by Schram et al. [18], the average value of the rut depths at 4th, 5th, 6th, 7th, and 8th points along the wheel path was considered as the HWTD test result for this study. As this equipment is capable of testing a pair of samples simultaneously, average of the two parallel HWTD tests (a total of 4 tests for each asphalt concrete mixture) was considered as the final result for further analysis. In addition, the targeted air void percentage assigned for all tested samples was fixed within 5 to 7 %, as the state of New Mexico assigned a specified air void content of 6 % as the design parameter.

Plot of rut depth vs. number of wheel passes are analyzed to predict rutting and stripping susceptibility. Fig.3 includes a post compaction consolidation (PCS), a creep slope (CS), a stripping slope (SS), and a stripping inflection point (SIP).

PCS occurs within 1,000 number of wheel passes and simulates initial densification of pavement mixtures when traffic movement is allowed on a newly constructed pavement. CS relates the rutting susceptibility through measurement of permanent deformation which occurs due to plastic flow. SS relates the stripping susceptibility of the mixtures. A lower value of CS and SS indicates characteristics of decreased rutting and stripping resistance of tested samples [19]. If the plot does not include a SS or a SIP, the mixture has adequate moisture damage resistance.

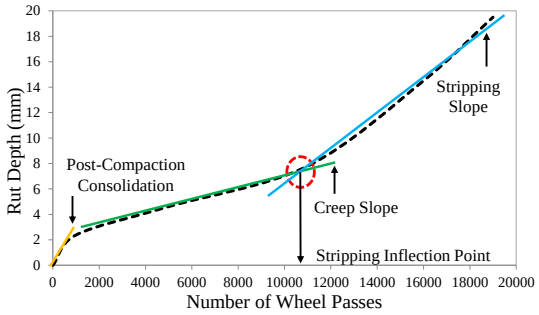


Fig.3 Schematic of HWTT results

3.3 Test Procedures for Binder Evaluation

In order to evaluate the effects of warm mix additives and recycled materials, extraction and recovery of asphalt binder from asphalt concrete was the approach considered. Extraction was performed following AASHTO D2172 and AASHTO D5404, respectively. The solvent used in this process is trichloroethylene.

AASHTO T 315-10 was followed to perform PG temperature sweep tests at 50°C in order to determine the G*/sinδ values of the extracted binders. G* is the complex shear modulus, and δ is the phase angle of the binder which depend on the temperature and frequency.

In addition, MSCR tests were conducted to determine the percent recovery (%R) and non-recoverable creep compliance (J_{nr}) values for 3200 pa of the binders, in accordance to AASHTO T 350-14. J_{nr} represents the amount of non-recoverable strain due to unit applied stress and %R describes the percentage of elastic recovery after removal of the load.

4. RESULTS AND ANALYSES

4.1 Hamburg Test Results

Fig.4 shows HWTT analysis of the SPS-10 pavement mixtures, where the average rut depth values of four test replicates per mixture has been taken as the symbolic rut depth value. As shown in Table 2, an analysis of variance (ANOVA) was conducted to observe the differences in the test replicates of each mixture. The analysis results demonstrate no statistical significant difference in rut values, as the *p*-value was found to be greater than 0.05 for each of the mixtures.

It is observed that all five mixtures has have a representative PCSs and CSs. However, stripping phase was not reached for any of the mixes, indicating no incidence of damage due to the effects of moisture. This may be attributed to the incorporation of 1% versabind® in these mixtures; a well-known anti-stripping agent. According to research conducted by Hill [20], it was observed that the incorporation of RAP to WMA has the potential to improve the performance of these type of mixtures at intermediate to high temperatures.

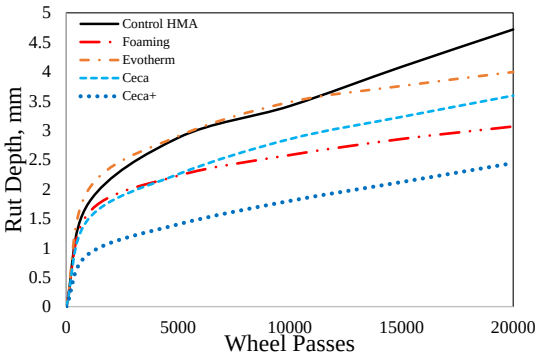
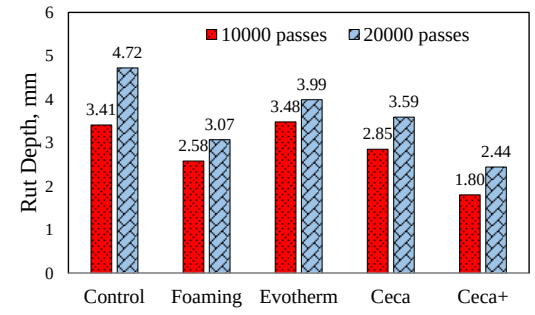


Fig.4 Hamburg test results for evaluated mixes

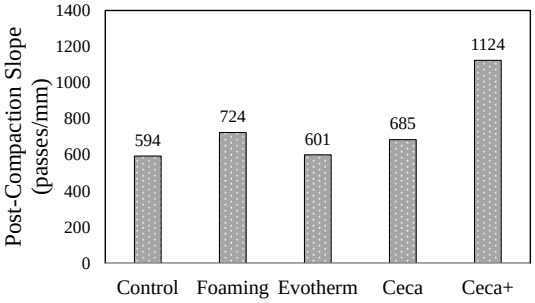
Table 2 Summary of HWTD results

Mix Code	Air Void (%)	ANOVA (*p*-value)
Control	5.85	0.9300
Foaming	5.70	0.5376
Evotherm®	5.99	0.7953
Cecabase®	6.70	0.9735
Cecabase®+	6.73	0.5095

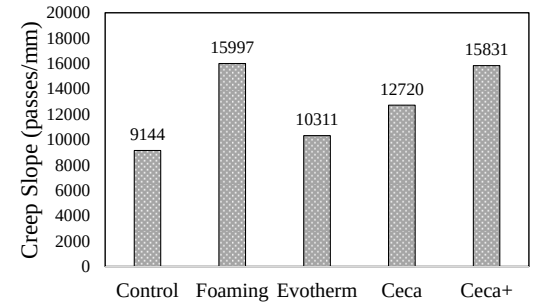
Fig. 5 summarized the HWTT test results. In reference to Fig.5a, a comparable trend was observed for rut depth measurements at 10,000 number of wheel passes with slightly lower values with respect to values from 20,000 wheel passes. While comparing the final rut values, results display a significant reduction in rutting susceptibility for Cecabase®+ (2.44 mm) mixture in comparison to control HMA (4.72 mm). However, between two Cecabase mixtures, Cecabase® without polymers exhibited a slightly higher rut depth (3.59 mm). On the contrary, Cecabase®+ is polymerized, resulting in a harder mixture and consequently has lowest rut depth among all texted mixtures. This specific circumstance exhibits the effect of linking warm mix additives with polymers.



(a) Rut depths at 10000 & 20000 passes



(b) Post-compaction slope



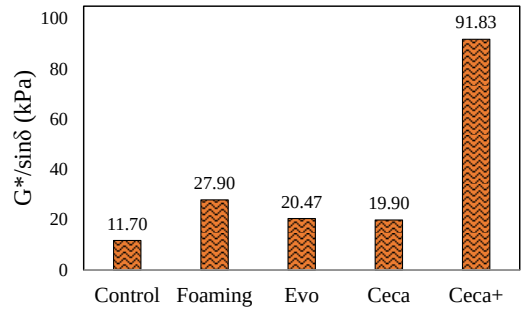
(c) Creep slope

Fig.5 Hamburg test results for evaluated mixes

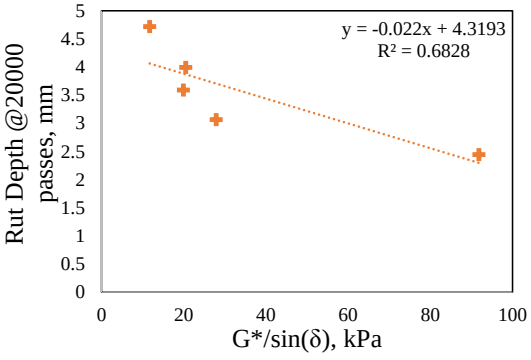
Fig.5b represents the PCSs of the mixtures. It indicates that Cecabase®+ has significantly higher PCS compared to other mixture. On the other hand, base mixture has the lowest PCS among the test mixtures. Similarly, CSs of these mixtures also illustrate this similar trend (as shown in Fig.5c) except for Terex® foaming mixture. In foaming WMA, trapped air bubble might be squeezed rapidly in post-compaction phase and after that the mixture became harder thus having higher CS. From the HWTT results, it is evident that all WMA mixtures performed well against rutting compared to control mixture.

4.2 PG Rutting Parameter – G*/sinδ

Superpave PG binder specification uses G*/sinδ value as a representative parameter to evaluate the rutting susceptibility of a binder. This parameter is developed on basis of minimizing the dissipation energy after each cycle of loading. A lower G*/sinδ represent the higher rutting susceptibility and vice-versa. The PG test results of the extracted binders are shown in Fig.6. All forms of warm mix modification was observed to increase the PG rutting parameter (Fig.6a). For example, G*/sinδ value for binders with Terex® foaming, Evotherm®, Cecbase®, and Cecabase®+ was found to be approximately 27.90, 20.47, 19.90, and 91.83 kPa, respectively, compared to 11.70 kPa for control HMA. Out of the four additives, results show that the addition of Cecabase® with polymerization increased G*/sinδ substantially, indicating the highest rutting resistance with this modification arrangement. From these results, Cecabase®+ is recognized to be the most effective additive in improving rutting resistance followed by Terex® foaming, Evotherm®, and Cecabase® unmodified. A simple linear regression analysis was done to see the correlation between G*/sinδ of binder and rut depth of mixture. Based on the simple regression analysis (Fig.6b), a correlation of R^2 = 0.68 was observed between the maximum rut depth and rheological parameter values of these mixtures. This indicates that the PG rutting parameter is incapable to represent the rutting performance of the mixture.



(a) G*/sinδ values of extracted binders



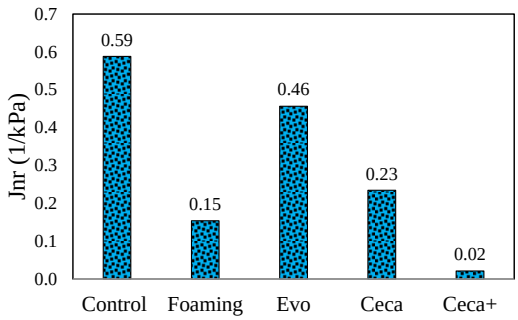
(b) Rut depth vs. G*/sinδ

Fig.6 G*/sinδ parameter results

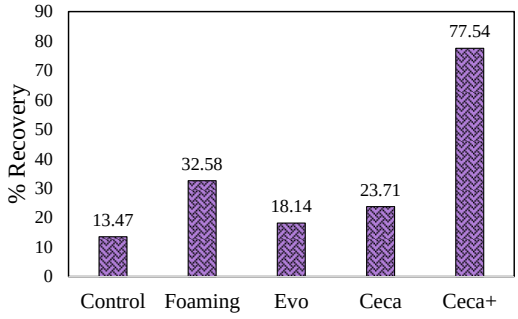
4.3 MSCR Rutting Parameters – J_{nr}, %R

Besides the PG test, researchers are now using MSCR test to evaluate the elastic response to characterize the rutting potential of a binder in non-

linear viscoelastic region [21]. Therefore, this study also performed the MSCR test on the extracted binders. Fig.7 shows the results from the MSCR test. Found J_{nr} values for 3200 Pa stress level are summarized in Fig.6a. A higher J_{nr} value of a binder represents that the binder is prone to accumulate more non-recoverable strain (or damage). The J_{nr} value of control HMA was found to be 0.59 kPa^{-1}. The J_{nr} values of the extracted binders with Terex®, Evotherm®, Cecabase®, and Cecabase®+ was found to be 0.15, 0.46, 0.23, and 0.02, respectively. Lower J_{nr} values were observed for all WMA modified mixtures in comparison to control HMA. This indicates increased rut resistance. Fig.7b shows the %Recovery for all extracted binders. A higher %Recovery represents more elastic property and vice-versa. The % Recovery value of the control sample was found to be 13.47. The % Recovery values of the extracted binders with the presence of Terex®, Evotherm®, Cecabase®, and Cecabase®+ was found to be 32.58, 18.14, 23.71, and 77.54, respectively. This also indicates that all WMA samples have increased rutting resistance compared to the control sample. Based on the lowered J_{nr} and heightened %Recovery values from the incorporation of Cecabase®+, the influence of polymerization is exhibited through the decreased rutting potential.



(a) Non-recoverable creep compliance

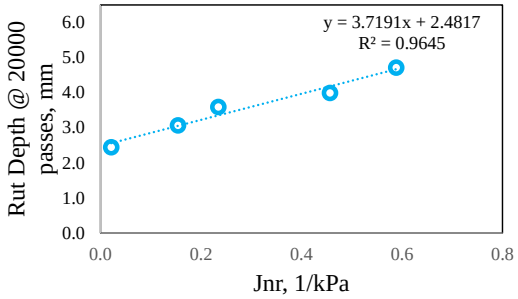


(c) % Recovery

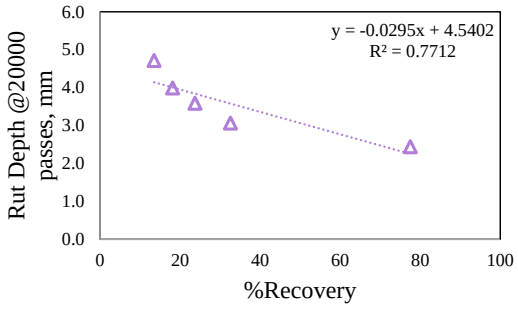
Fig.7 MSCR parameter results

Again, simple linear regression analyses were performed between the two parameter results obtained from this test method in contrast to HWTT rut depth, as shown in Fig.8. The correlation values of R^2 = 0.96 and R^2 = 0.77 were found for J_{nr} and % Recovery, respectively (Fig.8a and Fig.8b). Hence, indicating the non-recoverable creep compliance parameter as a reliable measure when it comes to evaluating rutting resistance, out of the MSCR parameters.

Based on the J_{nr} values, the order of rut resistance for the extracted binders can be seen as (i) Cecabase®+, (ii) Terex® Foam, (iii) Cecabase®, (iv) Evotherm®, and (v) Control. This ranking order shows that compared to the control HMA sample, WMA modification improves the rutting potential of the mixtures.



(a) Rut depth vs. J_{nr}



(b) Rut depth vs. %Recovery

Fig.8 Simple linear regression analysis of MSCR results with respect to HWTT

5. CONCLUSION

This study has evaluated the anti-rutting abilities of warm mix additives in asphalt concrete mixtures. The key findings drawn from this research are discussed below:

- All mixture samples performed better against rutting compared to control HMA sample. Among the WMA mixtures, Terex® (foaming) and Cecabase® samples exhibited better rutting resistance than Evotherm® sample. Cecabase®+ showed significant rutting resistance improvement due to presence of polymer. In HWTT mixture testing, stripping phase was not reached for all mixtures,

indicating ample damage resistance against the effects of moisture.

- It is also observed that the rutting resistance order of the extracted binders with the different WMA additives are almost identical among the three rheological rutting parameters. However this doesn't hold completely true for the warm mix additives of Evotherm® and Cecabase® unmodified. In the case of G*/sinδ, two additives examined under the specified measure indicate an opposite trend with respect to J_{nr}, % Recovery, and HWTD ranking results. Overall, the results show that ranking of rutting potential of binder depends on the rheological parameters and types of additives used. Thus, it can be said that binder's rutting susceptibility ranking might vary based on the Superpave and other rheological rutting parameters.
- Based on the simple regression analysis results, J_{nr} presents the best correlation ($R^2 = 0.96$) with rutting results obtained from HWTT.

It is recommended to conduct another study to evaluate the effects of higher percentages of RAP content. In addition, if the opportunity presents itself, the effects of these select additives on varying binder performance grades and gradation will provide good insight in evaluating the impact of WMA technology.

In addition, since these mixtures have physical site locations, it would be beneficial to assess the field performance of these pavement sections. In order to structure a comprehensive overview of the pavements rutting behavior over time, annual field rutting performance surveys should be collected with the use of pavement profiling systems for high-speed rut measurements. An alternative route to be considered is to conduct HWTD testing on field cored samples collected from pavement site locations and correlate findings with laboratory compacted specimens.

6. ACKNOWLEDGEMENT

This project is funded by New Mexico Department of Transportation (NMDOT) and Southern Plain Transportation Center (SPTC). The authors would also like to express their gratitude to the research bureau team of NMDOT.

7. REFERENCES

[1] Tutu, K.A. and Tuffour, Y.A., "Warm-Mix Asphalt and Pavement Sustainability: A Review", Open Journal of Civil Engineering, Vol. 6, No. 2, 2016, pp. 84.

[2] Jones, W., "Warm Mix Asphalt Pavements: Technology of The Future?", Asphalt, Vol. 19, No. 3, 2014.

[3] Button, J.W., Estakhri, C. and Wimsatt, A., "A Synthesis of Warm Mix Asphalt (No. FHWA/TX-07/0-5597-1)", College Station, TX: Texas Transportation Institute, Texas A & M University System, 2007.

[4] Akisetty, C.K.K., "Evaluation of Warm Asphalt Additives on Performance Properties of CRM Binders and Mixtures", (Doctoral dissertation, Clemson University), 2008.

[5] Politano, L., "Warm Mix Asphalt-A Greener Alternative to Hot Mix Asphalt", 2012 Conference and Exhibition of the Transportation Association of Canada-Transportation: Innovations and Opportunities, 2012.

[6] Croteau, J.M. and Tessier, B., "Warm Mix Asphalt Paving Technologies: A Road Builder's Perspective", In Annual Conference of the Transportation Association of Canada, Toronto, 2008.

[7] Bahia, H.U., Hanson, D.I., Zeng, M., Zhai, H., Khatri, M.A. and Anderson, R.M., "Characterization of Modified Asphalt Binders in Superpave Mix Design", (No. Project 9-10 FY'96), 2001.

[8] Tabatabaee, H.A. and Bahia, H.U., "Establishing Use of Asphalt Binder Cracking Tests for Prevention of Pavement Cracking", Road Materials and Pavement Design, 15(sup1), 2014, pp.279-299.

[9] Pérez-Lepe, A., Martınez-Boza, F.J., Gallegos, C., González, O., Muñoz, M.E. and Santamarıa, A., "Influence of The Processing Conditions on The Rheological Behaviour of Polymer-Modified Bitumen", Fuel, Vol. 82, No. 11, 2003, pp.1339-1348.

[10] Morea, F., Agnusdei, J.O. and Zerbino, R., "Comparison of Methods for Measuring Zero Shear Viscosity in Asphalts", Materials and structures, Vol. 43, No. 4, 2010, pp.499-507.

[11] Yildirim, Y., "Polymer Modified Asphalt Binders", Construction and Building Materials, Vol.. 21, No. 1, 2001, pp.66-72.

[12] Moghadas Nejad, F., Azarhoosh, A., Hamedi, G.H. and Roshani, H., "Rutting Performance Prediction of Warm Mix Asphalt Containing Reclaimed Asphalt Pavements", Road Materials and Pavement Design, Vol. 15, No. 1, 2014, pp.207-219.

[13] Irfan, M., Waraich, A.S., Ahmed, S. and Ali, Y., "Characterization of Various Plant-Produced Asphalt Concrete Mixtures Using Dynamic Modulus Test", Advances in Materials Science and Engineering, 2016.

[14] Rahman, M.T., Burchett, T.J., Kargah-Ostadi, N. and Sassin, J.M., "Long-Term Pavement Performance: Preliminary Analysis of Constructed Warm-Mix Asphalt Overlay Projects", In Transportation Research Board 95th Annual Meeting (No. 16-5768), 2016.

[15] Van de Ven, M.F.C., Jenkins, K.J., Voskuilen, J.L.M. and Van Den Beemt, R., "Development of (Half-) Warm Foamed Bitumen Mixes: State of The Art", International Journal of Pavement Engineering, Vol. 8, No. 2, 2007, pp.163-175.

[16] Kristjánsdóttir, Ó., Muench, S., Michael, L. and Burke, G., "Assessing Potential for Warm-Mix Asphalt Technology Adoption ", Transportation Research Record: Journal of the Transportation Research Board, (2040), 2007, pp.91-99.

[17] Rashwan, M.H., "Characterization of Warm Mix Asphalt (WMA) Performance In Different Asphalt Applications", (Doctoral dissertation, Iowa State University), 2012.

[18] Schram, S., Williams, R. and Buss, A., "Reporting Results from the Hamburg Wheel Tracking Device." Transportation Research Record: Journal of the Transportation Research Board 2446, 2014, pp.89–98.

[19] Larrain, M.M.M. "Analytical Modeling of Rutting Potential of Asphalt Mixes Using Hamburg Wheel Tracking Device", (Master's Thesis), 2016.

[20] Hill, B., "Performance Evaluation of Warm Mix Asphalt Mixtures Incorporating Reclaimed Asphalt Pavement." (Doctoral dissertation, University of Illinois at Urbana-Champaign), 2011.

[21] Anderson, M., D'Angelo, J., and Walker, D., "MSCR: A better tool for characterizing high temperature performance properties." Asphalt, 25(2), 2010.

Copyright © Int. J. of GEOMATE. All rights reserved, including the making of copies unless permission is obtained from the copyright proprietors.