Technical Investigation of the Usability of Foamed Bitumen Stabilized Materials in Asphalt Pavements

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ABSTRACT

Asphalt recycling efforts are increasing in an effort to reduce the effects of high energy and raw material consumption in the asphalt sector. One of the most common methods for using old asphalt materials that still retain some value is recycling with foam bitumen. In practice, to prepare and evaluate cold mixes produced using foam bitumen, the indirect tensile strength (ITS) and resilient modulus (M_R) methods are generally used. Among these methods, the ITS is mostly applied for the evaluation of the optimum percentages of materials, and the M_R is used to evaluate the mixture performance. In these experiments, for cold mixes prepared with foam bitumen, the optimum foam bitumen values of the production series were first determined using ITS tests. Then, reproductions were created with these optimum values, and the M_R values were determined. It was found that the ITS and M_R values were significantly affected by the material gradation and showed the opposite trends for materials with the same gradation. The effect of the type of active filler was the same as the values of the mixtures on the ITS and M_R. In particular, the M_R results were affected by the bitumen grade. Based on the results of this study, evaluation limit values of 225 kPa for ITS_{DRY}, 150 kPa for ITS_{WET}, 70% for TSR, 400 MPa for M_R, and 0.21 for the layer coefficient are recommended for foam bitumen stabilized material (FBSM).

Keywords: Foam Bitumen Stabilized Material (FBSM); Layer Coefficient; Recycled Asphalt; Resilient Modulus (MR).

INTRODUCTION

Rapid industrial development has led to energy consumption and environmental problems (Xiao et al., 2018). Currently, agricultural products waste (Agwa et al., 2022; Azevedo et al., 2022), plastics (Fonseca et.al, 2022), glass (Ali et al., 2021; Kadhim et al., 2022; Hasani et al., 2022), demolition waste (Haque et, al., 2014), and other processes that create many different waste materials provide technical, environmental, and economic advantages in the construction sector. To reduce aggregate consumption and the need for binders in recycled asphalt pavements (Zaumanis et al., 2016; Kushwaha and Swami, 2019), products with binding properties such as cement, fly ash, lime and cutback bitumen are frequently used (Wang et al., 2018). Recycled asphalt, which can be used in all layers from the wearing course to the subbase course of the pavement, can retain its value as asphalt despite its reuse and recycling processes (McDaniel and Anderson, 2001; Hasan et al 2022). Particularly with on-site and cold recycling methods, significant gains have been achieved in terms of energy consumption, acidification, abiotic depletion of fossil fuels, and global warming (Turk et al., 2016).

The foam bitumen recycling process is a cold asphalt recycling method that is added to reclaimed asphalt pavement (RAP) material; by increasing the surface area of the bitumen and reducing its viscosity (Zhang et al., 2018), it can be mixed with cold and moist aggregates (Muthen, 1998). When water at ambient temperature is added to the hot bitumen, the water becomes trapped in the form of small bubbles in the bitumen, thus increasing the bitumen volume (Muthen, 1998; Hasan et al., 2017; Kumrawat and Deulkar, 2019). Sprayed foam bitumen is often dispersed as fine particles (Iwanski and Kowalska, 2019). A structure consisting of large aggregates partially coated with mastic droplets can be obtained (Jenkins, 2000; Fu et al., 2009). Therefore, material gradation is very important for foamed bituminous cold mixes.

Indirect tensile strength is commonly used to evaluate the potential fracture properties and moisture sensitivity of asphalt mixtures. The pre-conditioning dry indirect tensile strength (ITS_{DRY}) and post-conditioning wet indirect tensile strength (ITS_{WET}) values (Wirtgen, 2012; Diab and Enieb, 2018) and the tensile strength retained (TSR) parameter determined by the ratio of these two parameters can be used to calculate the damage caused by the moisture effect (Iwanski and Kowalska, 2019). For roads with an equivalent standard axle load > 6 million, limit values of ITS_{WET} of at least 100 kPa, ITS_{DRY} of at least 225 kPa, and TSR of at least 50 have been proposed by Wirtgen (2012). The higher the TSR, the better the ability of the asphalt mixture to resist moisture damage will be (Diab and Enieb, 2018; Kushwaha and Swami, 2019).

Another evaluation criterion, the resilient modulus, which is known as the elastic modulus based on recoverable strain under repeated loading (Witczak, 2003), also defines the resistance of pavement materials to flexible deformation under applied loads (Fu et al., 2009). Austroads (2011) stated that there are different approaches for the resilient modulus, and acceptable values are between 500 and 4000 MPa. According to Khosravifar et al. (2015), the structural capacity of a foam bitumen-stabilized material (FBSM) is located between that of the granular aggregate base and the hot mix asphalt when the appropriate design and application are selected.

Based on the literature, in this study, production specimens were fabricated with different penetration bitumen percentages, active filler products, and material gradations. The ITS values of the production specimens and optimum bitumen percentages of the production series were determined, and the resilient modulus values were evaluated for these optimum bitumen percentages. In addition, an ideal gradation range was proposed for the FBSM.

MATERIALS AND EXPERIMENTAL METHODS

The RAP material used in this study, which has a bitumen content of 3.54% and has been in service for approximately 15 y, has the Type-A gradation, as listed in Table 1 (Erten, 2020).

Table 1. Material gradations prepared for productions

Sieve Size		Gradation Type/Passing (%)				
mm	inch/no	Type-A	Type-B	Type-C	Type-D	Type-E
25	1	100	100	100	100	100
19	3/4	96	97	98	96	84
12.5	1/2	87	89	90	87	75
9.5	3/8	79	81	83	79	70
4.75	No. 4	58	62	67	58	58
2	No. 10	33	41	50	33	45
0.425	No. 40	9	18	32	11	28
0.18	No. 80	4	12	20	7	20
0.075	No. 200	1.6	6	12	4	12

The physical properties of the bitumens used in this study are listed in Table 2 (Erten, 2020).

Table 2. Basic properties of four bitumens and RAP binders

Experimental Results of Bitumens						Limit Values			
Properties	Penetration Grade								
	50/70	70/100	100/150	160/220	RAP Residue Bitumen	50/70	70/100	100/150	160/220
Penetration (25 °C) 0.1 mm	53.6	85.2	102.1	172	32.4	50-70	70-100	100-150	160-220
Softening Point (°C)	49.4	46.8	43.2	37.1	60.6	46-54	43-51	39-47	35-43
Specific Gravity (g/cm^3)	1.036	1.033	1.024	1.021	1.06	1.01-1.06	1.01-1.06	1.01-1.06	1.01-1.06

For materials recycled in practice, different gradations are encountered depending on the depth of scraping and purpose of the road during the initial construction. To represent these different situations, Table 1 lists five types of gradations. The black values in the table represent 100% RAP material, and the red values represent Type A gradation + new aggregate. To ensure a homogeneous distribution of foam bitumen in the mixture, fine material substitution is generally performed. Type E gradation was created using 10% RAP and 90% virgin material to represent material scraping from a bituminous surface treatment. Type D gradation, commonly used as proposed by Wirtgen, is similar to the Type A gradation, but more material passes through a 0.425 mm sieve. This difference between the two gradations is only important for observing the effect of increasing the fine material content on the ITS value.

For the experiments, penetration bitumens of 50/70, 70/100, 100/150, and 160/220 grades were selected to produce the bitumen foam and mixes, and a foam bitumen laboratory plant (WLB 10S and WLM 30) developed by Wirtgen was used.

For the production specimens, control of the optimum bitumen percentage was achieved with the ITS and TSR parameters from the series produced for each gradation type. For Type A gradation, mixtures of all bitumen grades were prepared with five different bitumen percentages (1.9%, 2.2%, 2.5%, 2.8%, and 3.1%).

If the bitumen percentage was high, the bitumen forms lumps, as reported by Thompson et al. (2009), instead of uniformly dispersing or coating the coarse aggregate (Figure 1, areas within the red square). The structure observed in the other parts of Figure 1 (Erten, 2020) corresponds to a more homogeneous bitumen distribution, as reported by Jones et al. (2008).

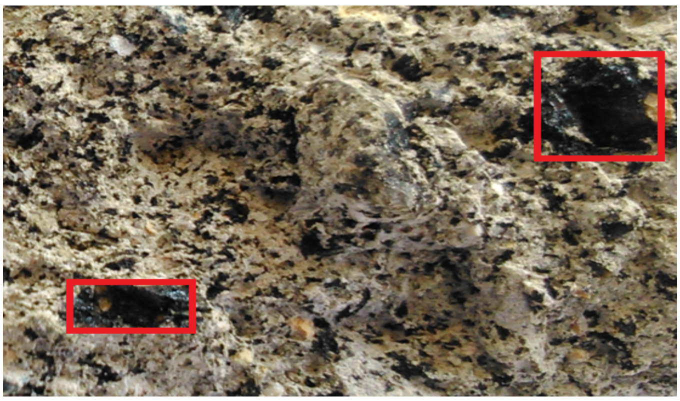


Figure 1. Different distribution regions of bitumen in the briquette internal structure

Because cement is often used as an active filler in foamed bituminous mixtures (Asphalt Academy, 2009; Jain and Singh, 2021; Fadmoro et al., 2022) only Portland cement was used as the active filler for all percentages. For the 70/100 bitumen grade, lime and fly ash mixtures were also prepared for the 2.5% bitumen specimen. The active filler ratio was chosen as 1% to prevent shrinkage cracking (Asphalt Academy, 2009).

Indirect Tensile Strength

Marshall briquettes with a diameter of four inches were prepared. The briquettes were removed from the molds the day after production and left to stand in a drying oven at 40 °C for 72 h. At the end of this period, three of the briquettes were broken to determine the ITS_{DRY} value. The three briquettes were also placed in a 25 °C water bath for 24 h to determine the ITS_{WET} value.

The ITS and TSR values were calculated using Equations (1) and (2), respectively (Wirtgen, 2012).

$$\text{ITS} = \frac{10^6 * 2 * P}{\pi * h * d}, \tag{1}$$

where P is the maximum load (kN), h is the briquette height (mm), and d is the briquette diameter (mm).

$$\text{TSR} = \frac{ITSWET}{ITSDRY} * 100 \tag{2}$$

Samples were prepared to determine the resilient modulus at the optimum bitumen values. If more than one bitumen percentage provided the limit values ($ITS_{DRY} > 225$ kPa and $ITS_{WET} > 100$ kPa), a lower bitumen percentage was preferred to increase the recycling benefit.

Resilient Modulus

The AASHTO T 307-99 (2012) procedure was used to determine the resilient modulus of the prepared samples; the method employed a vibrating compaction hammer at an optimum water content of 152 mm in diameter and 315 mm in height. The tests were carried out in a triaxial chamber with half-sine wave loading comprising 0.1 s loading and 0.9 s resting. A total of 995 pre-conditioning loads were applied, and the subsequent five loads were used to obtain the average resilient modulus; the same process was repeated for every 100 loads.

The resilient moduli of the production specimens were calculated using Equation (3) (Witczak, 2003) for each sequence. Then, using the confining stress and deviatoric stress applied to the sample in each sequence, the bulk stresses were calculated according to Equation (4) and the k-Θ model was calculated (Equation (5)).

$$M_R = \frac{\sigma_d}{\varepsilon_r}, \tag{3}$$

where M_R is the resilient modulus, σ_d is the deviatoric stress, and ε_r is the resilient strain (axial).

$$\Theta = \sigma_1 + \sigma_2 + \sigma_3 = \sigma_1 + 2\sigma_3 = 3\sigma_3 + \sigma_d, \tag{4}$$

$$M_R = K_1 \cdot (\Theta)^{K2}, \tag{5}$$

where Θ is the bulk stress, and K_1 and K_2 are experimentally derived constants (Huang, 2003).

Using Equation (6) (AASHTO, 1993; Schwartz and Khosravifar, 2013), layer coefficients of the FBSM production specimens were determined.

$$a = 0.249 \times \log E_{BS} - 0.977, \tag{6}$$

where E_{BS} is the resilient modulus (psi).

RESULTS AND DISCUSSION

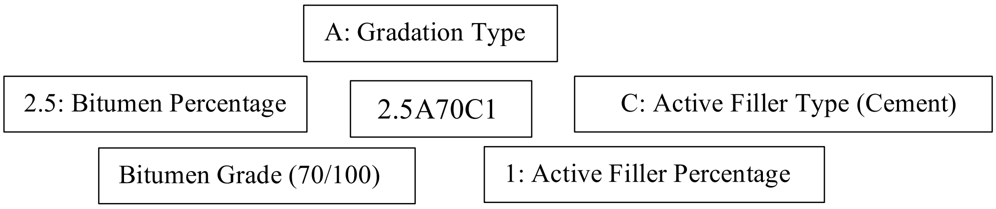
The numerical values of the ITS and resilient modulus for the optimum bitumen percentages of the production series are presented in Table 3 (Erten, 2020).

Table 3. Test results for production series

Specimen Code	Mean ITS_{DRY} (kPa)	Mean ITS_{WET} (kPa)	TSR %	M_R (MPa)	Layer Coefficient (a)
2.5A70C1	244.26	243.52	99.696	399.266	0.21
2.2A50C1	270.2	256.38	94.885	539.735	0.24
1.9A100C1	264.82	214.04	80.826	403.582	0.21
1.9A160C1	251.05	232.64	92.668	334.901	0.19
2.2B70C1	264.55	224.88	85.004	197.908	0.13
1.9C70C1	272.97	257.42	94.303	150.538	0.10
1.9D70C1	253.46	223.5	88.181	440.875	0.22
1.9E70C1	345.66	282.16	81.629	209.411	0.14
2.5A70HL1FA1	197.34	258.51	131.001	351.439	0.20
2.5A70HL1	135.28	189.62	140.164		
2.5A70FA1	119.9	113	94.25		

Because the ITS values are very low when hydrated lime (HL) and fly ash (FA) are used as active fillers, a resilient modulus test was not performed in these production series.

Sample coding for productions:



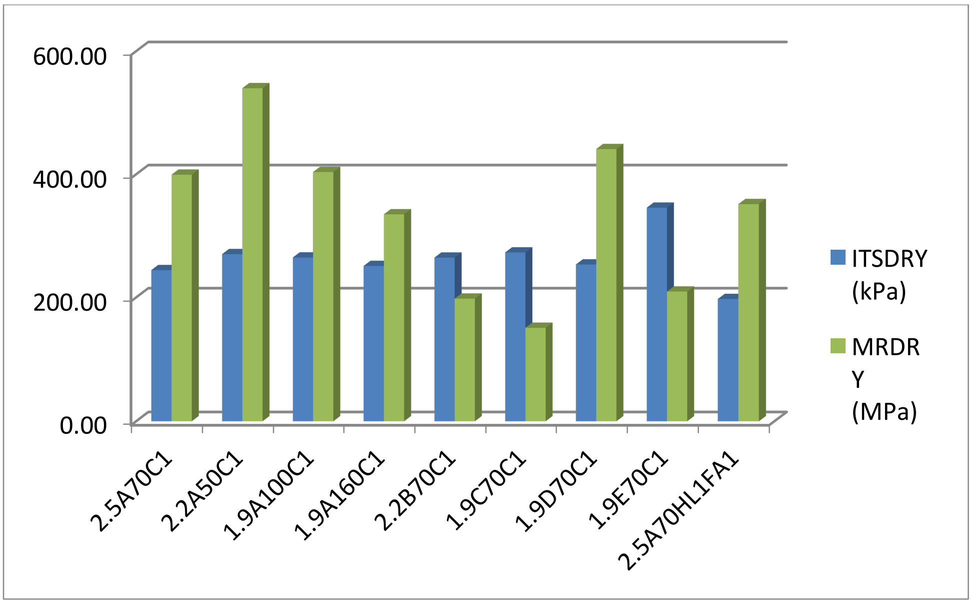


Figure 2. Comparison of M_R and ITS values for production series

As indicated in Table 3 and Figure 2 (Erten, 2020), in some production series, the TSR was close to or greater than 100%. These results, which are higher than the TSR values recommended in Section 1, can be explained by the fact that water curing accelerates the hydration process.

Regardless of the bitumen grade and percentage, the cemented production series performed better in terms of both ITS and M_R than the other active fillers.

While the ITS values of 160 penetration production for the Type A gradation were similar to those of other bitumen grades, the lower resilient modulus value indicates that the decrease in bitumen viscosity negatively affected the material stability. Because bitumen is more viscous than other bitumen grades in the production with 50/70 grade bitumen, the deformation resistance of the samples increased.

Using more fines of the No. 4 sieve material in the mixture increased the ITS value slightly, but it also caused a decrease in the resilient modulus and consequently in the coefficient layer.

In the Type E gradation, 90% of the material was formed from new aggregate, which also affected the resilient modulus negatively. In this situation, although the old bitumen in the RAP material was aged, it could add flexibility to the mixture. Yan et al. (2014) showed that there was still some activity in the aged bitumen in RAP materials. Similarly, Alam et al. (2010) and Hasan et al. (2018) reported that as the RAP content in base course materials increased, the value of the resilient modulus also increased.

Although there was no cement in the 2.5A70HL1FA1 production series and the ITS_{DRY} value was lower than that of the cemented production series, the resilient modulus value was high. This result reveals that the combination of different active fillers yields positive results in terms of mixture stability.

Increasing the percentage of fine materials performed well only in terms of the moisture damage (ITS). In terms of the resilient modulus, the opposite trend was observed. Therefore, contrary to the requirement for at least 5% No. 200 sieve material generally encountered in the literature, an ideal gradation range is proposed in Table 4 (Erten, 2020) according to the resilient modulus values.

Table 4. Material gradations recommended for FBSM based on the experimental results

Sieve Size (mm)	Passing (%)
37.5	100
25	98-100
19	90-97
12.5	78-89
9.5	70-81
4.75	50-60
2	28-36
0.425	8-16
0.18	4-10
0.075	1-6

The gradation recommended for the FBSM was compared with the plant mix base course (PMBC) and bituminous base course (BBC) gradations given in the Turkey Highway Technical Specifications (2013), as shown in Figure 3 (Erten, 2020).

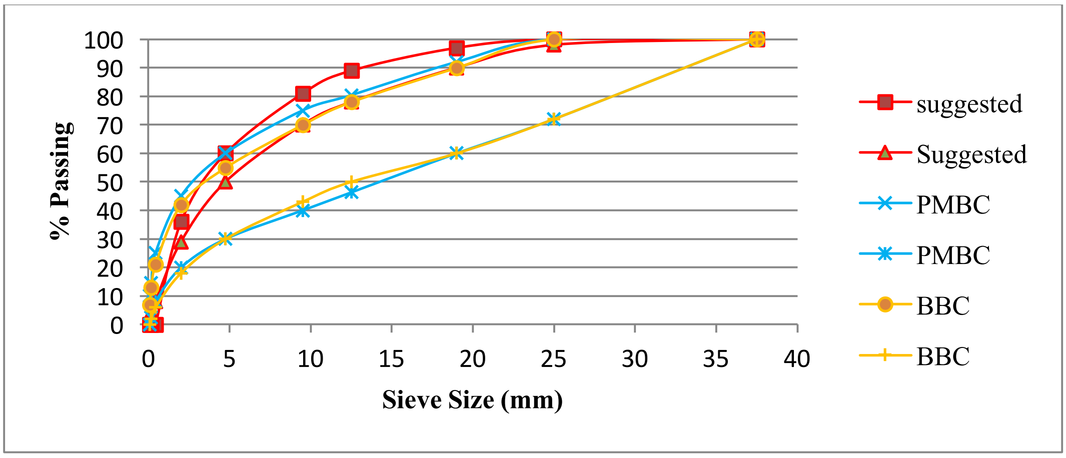


Figure 3. Comparison of the recommended gradation for FBSM with the PMBC and BBC gradations

This gradation offers several practical advantages. Among these advantages, FBSM has a fine gradation because the scraping material is broken during the recycling process of existing pavements, and the RAP material contains binder and wearing course materials. In addition, it is easy to address the fine material deficit, which is likely to be encountered only under the No. 40 sieve and can be complemented with new aggregate from the outside.

CONCLUSIONS AND RECOMMANDATIONS

In this study, the effect of variables such as the gradation, bitumen grade, bitumen percentage, and active filler type on the indirect tensile strength (ITS) and resilient modulus (M_R) of foam bitumen stabilized materials (FBSM) was investigated experimentally. The conclusions are summarized below.

- The ITS values are quite high when cement was used as an active filler in production, and it is considered appropriate to use cement for this application.
- Based on the obtained results, minimum limit values of 225 kPa for the ITS_{DRY} value, 150 kPa for the ITS_{WET} value, and 70% for the TSR value are considered appropriate.
- The resilient modulus value of the 160/220 bitumen grade is lower than those of the other bitumen grades. Therefore, other bitumen grades are more suitable for FBSM production.
- The layer coefficient results listed in Table 3 give the impression of a stabilized granular layer rather than bituminous mixtures for the FBSM.
- An ITS_{DRY} value exceeding 500 kPa indicates asphaltic behavior (Wirtgen, 2012); in this study, no production series could reach an ITS_{DRY} value of 500 kPa.
- The material gradation has a more significant effect on the resilient modulus results than on the ITS values. It is observed that more fines over the No. 4 sieve and coarse material under the No. 4 sieve are beneficial in terms of the resilient modulus results.
- According to the results, the pavement section shown in Figure 4 (Erten, 2020) appears to be applicable for FBSM according to the traffic load expected to be encountered in the application area. However, the risk of shrinkage cracks should be controlled for these materials with hydraulic binders.

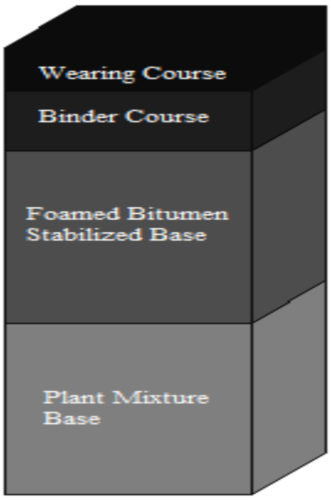


Figure 4. Recommended pavement cross section for cold in-place recycling with foam bitumen

- The results of the production in which fly ash and lime were used together are similar to those for cement. Therefore, the expansion of such combinations is recommended for future studies. However, it is not recommended to use active fillers alone, other than cement.
- It is recommended that performing ITS control will be sufficient for 1.8%–2% and 2.2% bitumen contents.
- Based on the results, 400 MPa M_R and 0.21 layer coefficient values are recommended.
- To maintain the resilient modulus and layer coefficient above the recommended limit values, the values listed in Table 4 for FBSM are considered as the ideal gradation.

In this study, FBSM was evaluated technically, and it was concluded that it can serve as an effective method to contribute to sustainable transportation.

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REFERENCES

AASHTO T 307-99, 2012. Determining the Resilient Modulus of Soils and Aggregate Materials. American Association of State Highway and Transportation Officials, Washington DC.

AASHTO, 1993. Guide For Design Of Pavement Structures. American Association of State Highway and Transportation Officials, Washington DC.

Agwa, I.S., Zeyad, A.M., Tayeh, B.A., Adesina, A., Azevedo, A.R.G. de, Amin, M., Nyarko, M., H. 2022. A comprehensive review on theuse of sugarcane bagasse ash a supplementary cementitius material to produce eco-friendly concretes. materialstoday:PROCEEDINGS.

Alam, T.B., Abdelrahman, M., Schram, S.A. 2010. Laboratory Characterization of Recycled Asphalt Pavement As a Base Layer. International Journal of Pavement Engineering, 11(2), 123e131.

Ali, S., Iqbal, S., Room, S., Ali, A., Rahman, Z.U., 2021. Value added usage of granular steel slag and milled glass in concrete production. Journal of Engineering Research, 9(1), 73-85.

Asphalt Academy, 2009. Technical Guideline: Bitumen Stabilised Materials, TG2 Second edition, ISBN 978-0-7988-5582-2

Austroads, 2011. Review of Foamed Bitumen Stabilisation Mix Design Methods, Report No: AP-T178/11, 37p.

Azevedo, A.R.G. de, Amin, M., Nyarko, M.H., Agwa, I.S., Zeyad, A.M., Tayeh, B.A., Adesina, A. 2022. Possibilities for the application of agro-industrial wastes in cementitious materials: A brief review of the Brazilian perspective. Cleaner Materials, 3 (2022).

Diab, A. & Enieb, M. 2018. Investigating Influence of Mineral Filler at Asphalt Mixture and Mastic Scales.International Journal of Pavement Research and Technology, 11, 213–224.

Erten, K. M., 2020. Köpük Bitüm ile Yerinde ve Soğuk Geri Kazanılmış Bitümlü Sıcak Karışımların Karayolunda Kullanılabilirliği ve Performansının Araştırılması, Süleyman

Demirel University, Ph.D. Thesis, 169p., Isparta, Turkey.

Fadmoro, O.F., Kar, S.S., Tiwari, D. 2022. Characterisation of Foam Bitumen Mixes with Diffrent RAP Content at Elevated Mixing Temperature Using Design of Experiment (DOE) Approach, International Journal of Pavement Engineering, DOI: 10.1080/10298436.2021.2020785

Fonseca, M., Capitão, S., Almeida, A., Santos, L.P. 2022. Influence of Plastic Waste on the Workability and Mechanical Behaviour of Asphalt Concrete. Applied Sciences, 12(4), 2146.

Fu, P., Jones, D., Harvey, J.T., Bukhari, S.A. 2009. Laboratory Test Methods for Foamed Asphalt Mix Resilient Modulus. Road Materials and Pavement Design, 10:1, 188-212.

Haque, M.N., Al-Yaqout, A.F., Sreekla, V., El-Hawary, M., 2014. Characteristics of Recycled Aggregate Concretes Produced in Kuwait : a case study. Journal of Engineering Research, 2(4), 15-31.

Hasan, A., Hasan, U., Whyte, A., Jassmi, H., A., 2022. Lifecycle Analysis of Recycled Asphalt Pavements: Case Study Scenario Analyses of an Urban Highway Section. CivilEng, 3(2), 242-262.

Hasan, M.M., Islam, M.R., Tarefder, R.A. 2018. Characterization of Subgrade Soil Mixed with Recycled Asphalt Pavement. Journal of Traffic and Transportation Engineering (English Edition), 5(3):207e214.

Hasan, M.R.M., You, Z., Yang, X. 2017. A Comprehensive Review of Theory, Development, and Implementation of Warm Mix Asphalt Using Foaming Techniques. Construction and Building Materials, 152, 115–133.

Hasani, H., Soleymani, A., Nasseri, H.R., Zadanbeh, M.K., Azizi, M.B. 2022. A Comprehensive Review of Utilizing Crushed Waste Glass as Green Construction Material. 2nd. International Conference on Architecture, Civil Engineering, Urban Development, Environment and Horizons of Islamic Art In the Second Step Statement of the Revolution

Tabriz Islamic Art University.

Iwanski, M. & Kowalska, A.C. 2013. Laboratory Study on Mechanical Parameters of Foamed Bitumen Mixtures in the Cold Recycling Technology. Procedia Engineering, 57, 433 – 442.

Jain, S. & Singh, B. 2021. Cold Mix Asphalt: An Overview. Journal of Cleaner Production, 280, 20p.

Jenkins, K.J. 2000. Mix Design Considerations for Cold and Half-cold Bituminous Mixes with Emphasis on Foamed Bitumen. Ph.D.Thesis. University of Stellenbosch, 368p South Africa.

Jones, D., Fu, P., Harvey, J.T., Halles, F. 2008. Full Depth Pavement Reclamation with Foamed Asphalt. Report no: UCPRC-RR-2008-07, 271p.

Kadhim, M.A., Shakir, A.B., Dulaimi, A., Sadique, M., Nageim, H.A., Kafaji, M.A., Yasari, R.A. 2022. Developing a sustainable, post treated, half warm mix asphalt for structural surface layer. Construction and Building Materials, 342-Part A.

Khosravifar, S., Schwartz, C.W., Goulias, D.G. 2015. Mechanistic Structural Properties of Foamed Asphalt Stabilised Base Materials. International Journal of Pavement Engineering, 16:1, 27-38.

Kumrawat, S. & Deulkar, V. 2019. A Research on Foamed Bitumen. International Research Journal of Engineering and Technology (IRJET), 6(5) 6969-6974

Kushwaha, P. & Swami, B.L., 2019. A Study on Moisture Susceptibility of Foamed Bitumen Mix Containing Reclaimed Asphalt Pavement. Transportation Infrastructure Geotechnology, 6:89-104.

McDaniel, R. & Anderson, R.M. 2001. Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Technician's Manual. National Cooperative Highway Research Program, NCHRP Report 452.

Muthen, K.M., 1998. Foamed Asphalt Mixes Mix Design Procedure. Report No: CR-98/077.

Schwartz, C.W. & Khosravifar, S. 2013. Design and Evaluation of Foamed Asphalt Base

Materials. Report no: SP909B4E, 86p.

Thompson, M.R., Garcia, L., Carpenter, S.H. 2009. Cold in Place Recycling and Full Depth Recycling with Asphalt Products (CIR&FDRWAP). Report no: FHWA-ICT-09-036, 28p.

Turk, J., Pranjic, A.M., Mladenovic, A., Cotic, Z., Jurjavcic, P. 2016. Environmental Comparison of Two Alternative Road Pavement Rehabilitation Techniques: Cold-In-Place-Recycling Versus Traditional Reconstruction. Journal of Cleaner Production, 121, 45-55.

Turkey highway technical specifications, 2013. General Directorate of Highways, Ankara.

Wang, Y., Leng, Z., Li, X., Hu, C. 2018. Cold Recycling of Reclaimed Asphalt Pavement Towards Improved Engineering Performance.Journal of Cleaner Production,171,1031-1038.

Wirtgen, 2012. Cold Recycling – Wirtgen Cold Recycling Technology, Wirtgen Cold Recycling Manual, 368p, Germany.

Witczak, M.W. 2003. Harmonized Test Methods For Laboratory Determination of Resilient Modulus For Flexible Pavement Design. National Cooperative Highway Research Program, Final Report.

Xiao, F., Yao, S., Wang, J., Li, X., Amirkhanian, S. 2018. A Literature Review on Cold Recycling Technology of Asphalt Pavement. Construction and Building Materials, 180, 579-604

Yan, J., Zhu, H., Zhang, Z., Gao, L., Charmot, S. 2014. The Theoretical Analysis of the RAP Aged Asphalt Influence on the Performance of Asphalt Emulsion Cold Recycled Mixes. Construction and Building Materials, 71, 444–450.

Zaumanis, M., Mallick, R.B., Frank, R. 2016. 100% Hot Mix Asphalt Recycling: Challenges and Benefits. Transportation Research Procedia, 14, 3493 – 3502.

Zhang, Z., Cong, C., Xi, W., Li, S. 2018. Application Research on the Performances of Pavement Structure with Foamed Asphalt Cold Recycling Mixture. Construction and Building Materials, 169, 396-402.