CETRA2024 15-17 May 2024, Cavtat, Croatia
8th International Conferenceon Road and Rail Infrastructure

# EXPERIMENTAL INVESTIGATION ON THE EFFECT OF CRUMB RUBBER ON THE MECHANICAL BEHAVIOUR OF STONE MASTIC ASPHALT (SMA)

**Mahdi Zakerzadeh, Babak Shahbodagh, Nasser Khalili**
*The University of New South Wales, School of Civil and Environmental Engineering, Sydney, Australia*

## Abstract

The utilisation of crumb rubber through a dry process addresses the challenges of tyre recycling and promotes environmental sustainability. This study aimed to investigate the mechanical behaviour of the Crumb Rubber Stone Mastic Asphalt (CR-SMA) mixture. The response surface methodology (RSM) is adopted to explore the impact of independent variables, such as binder content, Crumb Rubber (CR) content, processing time, and CR size, on the variables controlling the mechanical response of the mixture. To comprehensively evaluate the data, the moisture susceptibility, resilient modulus, and fracture energy of the asphalt mixtures are studied using Analysis of Variance (ANOVA). The study successfully achieved an optimum CR-SMA mixture design by enhancing resistance to moisture damage, resilient modulus, and fracture energy, contributing to an improved understanding of the mechanical performance criteria. A quadratic polynomial model aligned with experimental results is proposed, providing reliable predictions of the material performance with an acceptable level of accuracy. These findings offer a valuable roadmap for future strategies in construction, maintenance, and rehabilitation, particularly within the domain of rubberised SMA pavements.

*Keywords: stone mastic asphalt (SMA), recycled tyre rubber, response surface methodology (RSM), dry-process, rubberised asphalt mixture*

## 1 Introduction

Recycling waste tyres is a crucial global environmental challenge, with annual disposal of over 1.5 billion tyres reaching the end of their service life worldwide [1]. Faced with limitations in disposal space and escalating environmental concerns, many efforts have been undertaken to promote the recycling of used vehicle tyres, recognizing them as a potential source of industrial waste. As an effective and sustainable remedy to address this issue, the production of Crumb Rubber (CR) from these waste tyres has been recognised as a viable solution. The incorporation of CR as a modifier into asphalt mixtures offers an environmentally friendly alternative and also presents a practical means of repurposing waste tyres into a valuable resource, thereby contributing to the broader objectives of waste reduction and sustainable practices in the construction and road infrastructure sectors [2].
The incorporation of CR into asphalt mixtures can be accomplished through two primary methods: “wet” and “dry” modification. In the wet method, rubber is directly blended into bitumen, typically constituting a weight percentage ranging from 5% to 25% of the bitumen [2]. The addition of CR to bitumen serves to enhance the properties of the binder.

DOI: https://doi.org/10.5592/CO/CETRA.2024.1662

Specifically, at elevated temperatures, light fractions are absorbed into the polymer networks, causing the final bitumen to become stiffer while simultaneously swelling CR particles [3]. Nevertheless, if the temperature becomes excessively high or the duration is prolonged, the swelling process halts, leading to depolymerisation. Despite the advantages of the wet modification process, a significant challenge impeding the widespread use of CR-modified asphalt binders. These challenges include storage stability, increased energy consumption attributed to the extended reaction time and high mixing temperatures, potential difficulties in binder pumping, and the requirement for advanced mixing equipment [2, 4, 5].

On the other hand, the dry method involves blending CR particles with aggregates before adding bitumen, serving as a replacement for fine aggregates in asphalt mixtures. However, a short duration of the mixing process in the dry method may result in insufficient interaction between the bitumen and CR particles [6, 7]. Currently, the focus of research and field practices predominantly revolves around the wet process, with limited dry process application. The dry process does offer certain advantages, particularly in terms of a more straightforward protocol and the ability to use higher amounts of rubber [8]. Despite these advantages, mixtures prepared through the dry process also exhibit certain drawbacks. These include issues related to volume instability and reduced strength stemming from the incorporation of CR particles [9, 10].

The inherent gap-graded structure of Stone Mastic Asphalt (SMA), characterised by its elevated bitumen content, poses a challenge with regard to binder drainage. Generally, polymers and fibres serve as vital components in preventing binder drainage and elevating the overall performance of SMA. However, some studies [11-13] have indicated a promising alternative: incorporating CR to prevent drain-down in SMA and gap-graded asphalt mixtures, effectively substituting fibres and polymers. This approach reduces production costs and aligns with the global shift towards sustainable practices.

Despite its potential benefits, the application of CR through the dry process in SMA is currently constrained. In an evaluation by Feiteira Dias et al. [14], the mechanical performance and volume instability associated with asphalt mixtures processed through the dry method were assessed. It was demonstrated that increasing the mixing temperature to 190 °C and decreasing the rubber particle size to 0–0.6 mm effectively addressed these challenges. This protocol results in asphalt mixtures exhibiting performance comparable to samples prepared through the wet process. Xie and Shen [15] evaluated the performance of CR-SMA mixtures produced via wet and dry processes. Their assessment revealed that samples manufactured through the wet process performed better than those prepared using the dry process. Examining the interaction between asphalt binder and dry-processed rubber aggregate (30 mesh size), Shen and Li [16] revealed that large-sized molecules can be released from the rubber aggregate, akin to the wet process. However, a reduction in strength represents another challenge, impeding the broad implementation of mixtures produced through the dry process [17]. In another study, Mashaan and Karim [18] assessed the impact of CR added through the dry process on the rutting potential of SMA. The findings indicated that elevating the CR content up to 16% by the weight of bitumen resulted in the lowest strain and rutting depth. Another investigation by Mashaan et al. [19] focused on the fatigue life of SMA mixtures incorporating CR through the dry process. Consistent results were observed across both the dry and wet processes. The highest fatigue life and strain values were achieved by introducing 12% CR by the weight of the binder into the SMA mixture.

However, a noticeable gap exists in studies predicting the mechanical performance of rubberised SMA, particularly those utilising dry methods. This gap becomes apparent when considering various factors such as CR content, bitumen content, CR size, and processing time or short-term aging. This study aims to assess the influence of the key variables, including CR content, bitumen content, CR size, gradation, and processing time or short-term aging, on the performance of dry-added rubberised SMA mixtures.

The evaluation covers aspects like resistance to moisture damage, resilient modulus, and fracture energy. Utilising Response Surface Methodology (RSM) as an analytical tool, we explore the impact of independent variables and their interactions on the corresponding responses. A model based on the polynomial regression approach is proposed for the mechanical performance of CR-SMA, employing Analysis of Variance (ANOVA). The performance of the model is evaluated using RSM. The insights derived from this study provide a valuable roadmap for future construction, maintenance, and rehabilitation approaches, particularly in the context of rubberised SMA pavements.

# 2 Experiments

## 2.1 Materials

The samples were prepared using basalt aggregate obtained from a quarry in Sydney. The aggregate gradation chosen for SMA 10, featuring a nominal maximum aggregate size of 9.5 mm, adhered to the specifications outlined in Roads and Maritime Services (RMS) QA specification R121. Standard bitumen C320 supplied by Sami Bitumen Company served as the binder in this study. CR particles utilised in this study, obtained through an ambient process from Tyrecycle, comprised two variations distinguished by size and gradation. One type of CR consists of particles smaller than 2.36 mm, while the other comprises particles smaller than 1.18 mm.

## 2.2 Sample preparation

In this research, the preparation of CR-SMA mixtures involved the application of a dry process, adhering to the procedure recommended by AS/NZS 2891.2.1:2014 for asphalt mixture sample preparation. The heated aggregates were blended with CR particles, and the mixture underwent a 2-minute mixing phase to ensure the even dispersion of rubber particles. Subsequently, the heated asphalt binder was introduced into the mixture. To attain homogeneity, the components underwent an additional 3 minutes of mixing, maintaining a temperature of approximately 160 °C. The mixture was then placed in a tray, up to a thickness of 2 cm, and conditioned at 160 °C for the specified processing time, followed by a compaction process.
The Design Expert software was employed to design the experimental program and construct mathematical models for the fracture energy (FE), resilient modulus (RM), and tensile strength ratio (TSR) of CR-SMA. The Response Surface Methodology (RSM) was used to assess the impact of independent variables, including bitumen content, CR content, processing time, and CR particle size, on the variables. The experimental plan consisted of 24 distinct mixes designed with RSM, with corresponding levels assigned to the independent variables. Adopting a design strategy featuring five levels and quadratic models, a total of 24 treatments were considered in this experiment. This approach facilitates a thorough exploration of the interactions between independent variables and their influence on the mechanical performance of CR-SMA.

# 3 Results and discussions

The RSM is a statistical and mathematical technique employed to construct models, assessing the impact of independent variables and their interactions. In this study, a total of 24 tests were conducted to develop a regression model for the test results. Regression analysis was conducted using the data to establish the response function. The model underwent refinement through AIC backward reduction, involving the elimination of insignificant terms. Table 1 outlines the details of the proposed model.

Examining the ANOVA results generated through the application of the Two-Factor Interaction (2FL) and Quadratic model, it is observed that the obtained p-values are below the threshold of 0.05. Correspondingly, the F-values for the models were 29.78, 158.37, and 74.01, indicating the models' significance with a probability of only 0.01%. This implies that the models accurately represent the data within the 95% confidence interval. The 95% confidence interval ($p < 0.05$) was utilised to evaluate the significance of the models and variables. Furthermore, the outcomes provide a substantial degree of correlation ($R^2$) across all models, with values at 90.92%, 96.21%, and 98.27% for the Fracture Energy (FE), Resilient Modulus (RM), and Tensile Strength Ratio (TSR), respectively. The quadratic regression models accurately represent the observed data across the experimental range.
The models for FE, RM, and TSR for the CR-SMA mixture are provided in Table 2. It is apparent that the majority of key independent variables display a substantial significance in relation to the responses. Regarding FE, bitumen content emerges as the most significantly influential factor, followed by processing time, CR content, and CR size, in descending order. Despite CR size not individually demonstrating significance, its interaction with bitumen content markedly influences the FE performance of CR-SMA. This can be attributed to the effective interaction of smaller CR size with bitumen within the asphalt specimen, resulting in enhanced FE.
In evaluating RM, CR size is the most significant factor, succeeded by CR content, processing time, and bitumen content. The importance of CR size is clarified by its direct impact on the internal structure and compaction procedure within SMA. The size of CR particles is presumed to affect the interlocking mechanism between aggregates, introducing variations in the overall stiffness of the mixture. Moreover, the interdependence of CR content and bitumen content, along with CR size and bitumen content, emerges as additional influential factors affecting RM. The varied proportions of crumb rubber and bitumen induce modifications in the binder, leading to distinctive viscoelastic properties. This modification, in turn, influences the stiffness and elastic recovery of the CR-SMA, thereby contributing to alterations in the resilient modulus.
When considering TSR, bitumen content demonstrated the most significant impact, while CR content, processing time, and CR gradation followed in subsequent order of importance. As can be seen, all of the interplay between the processing time and and other factors highly affect the TSR performance of CR-SMA. The processing time plays a crucial role in facilitating the interaction between bitumen and rubber in CR-SMA. This interaction involves the absorption of light components by CR particles, leading to the formation of a polymeric network that enhances the TSR performance. Conversely, an extended processing time can intensify the impact of short-term aging, diminishing the TSR performance of CR-SMA.
For a visual representation of the results, Figure 1-Figure 3 depicts the graphs for the mechanical performance of CR-SMA, providing a comprehensive insight into the behaviour and trends observed in the models. As seen in the figure, RM markedly impact the mechanical behaviour of Crumb Rubber-Modified Stone Mastic Asphalt (CR-SMA). Fracture energy initially exhibited a positive correlation with the increase of binder content, reaching a peak at 7%, after which a gradual decline ensued. Simultaneously, the trajectory of CR content impact manifested a nuanced pattern, showing an incremental rise up to a critical CR content range of 1-1.5%, beyond which a pronounced reduction occurred.
It is noteworthy that the intricate interplay between bitumen content and CR content plays a pivotal role in determining RM. A reduction in bitumen content, approximately 6.4%, coupled with an increase in CR content, about 2%, demonstrated an augmenting effect on RM. This observation shows the significance of the synergistic relationship between CR and bitumen in influencing the resilient modulus of the CR-SMA mixture.

The impact of processing time on FE and RM exhibits divergent trends. The optimum point for FE occurs around 1-1.5 hours of processing time, suggesting a peak in fracture energy. In contrast, the trend for RM is characterised by a linear relationship, indicating that as processing time extends, the resilient modulus proportionally increases. Processing time serves as a critical parameter with the capacity to influence the breakdown of rubber particles during digestion, consequently exerting an impact on the properties of the asphalt mixture. Conversely, the short-term aging process facilitates the evaporation of volatile components, such as saturates and aromatics in bitumen, which ultimately affects the performance of CR-SMA. The influence of processing time on TSR varies notably depending on the binder content levels. In mixtures with high bitumen content, processing time demonstrates negligible impact. Conversely, in low bitumen content mixtures, extending the processing time markedly affects TSR. This disparity arises from the insufficient duration of shorter processing times to foster adequate interaction and strength development between the asphalt mixture and CR. Consequently, higher bitumen content enhances bonding and adhesion among components, thereby augmenting the moisture resistance of the asphalt mixture.
The interplay between CR content and processing time also reveals interesting patterns. A short processing time with high CR content results in reduced TSR. The limited processing duration impedes the formation of a robust polymeric network by rubber particles and the establishment of a well-defined polymeric structure. Consequently, the advantages of incorporating higher levels of CR content in the asphalt mixture are compromised. As processing times extend, TSR initially increases up to a threshold of around 1.5% CR content, followed by subsequent declines. The excessive introduction of CR has the potential to adversely impact the bond between bitumen and aggregates, leading to the aggregation of CR particles around aggregate surfaces and a subsequent reduction in the thickness of the binder film adhering to the aggregates. Moreover, the increase in the viscosity of bitumen resulting from excessive CR content contributes to reduced workability and impedes proper compaction.

**Table 1** The details of the regression models proposed for the mechanical performance of CR-SMA

| Response | Description | Sum of squares | Degree of freedom | Mean square | F-Value | Prob >F | Model |
|---|---|---|---|---|---|---|---|
| Fracture energy (FE) | Model | 1.63E+16 | 8 | 2.04E+15 | 29.78 | < 0.0001 | Reduced quadratic |
| | $R^2$ | 0.9408 | | | | | |
| | Adjusted $R^2$ | 0.9092 | | | | | |
| Resilient modulus (RM) | Model | 6.94E-11 | 8 | 8.68E-12 | 158.37 | < 0.0001 | Reduced quadratic |
| | $R^2$ | 0.9683 | | | | | |
| | Adjusted $R^2$ | 0.9621 | | | | | |
| Tensile strength ratio (TSR) | Model | 0.1202 | 10 | 0.012 | 74.01 | < 0.0001 | Reduced quadratic |
| | $R^2$ | 0.9827 | | | | | |
| | Adjusted $R^2$ | 0.9695 | | | | | |

**Table 2** The estimate of the coefficients for the regression models

| Factor | Intercept | A | B | C | D | AB | AC |
|---|---|---|---|---|---|---|---|
| **FE** | 2.23E+8 | -9.38E+6 | 1.43E+7 | 9.60E+6 | 2.51E+5 | - | - |
| **RM** | 7.10E-6 | -1.04E-6 | 5.19E-7 | -6.89E-7 | -9.86E-7 | 3.98E-7 | - |
| **TSR** | 4.50 | -0.0421 | 0.0528 | 0.0315 | 0.0129 | - | 0.0294 |

Table 2 The estimate of the coefficients for the regression models - continuation

| Factor | Intercept | BC | BD | CD | $A^2$ | $B^2$ | $C^2$ |
|---|---|---|---|---|---|---|---|
| **FE** | 2.23E+8 | – | -7.15E+6 | – | -3.97E+7 | -1.74E+7 | -1.82E+7 |
| **RM** | 7.10E-6 | – | 3.66E-7 | – | 2.13E-6 | 9.04E-7 | – |
| **TSR** | 4.50 | -0.0425 | – | 0.0162 | -0.0536 | -0.0276 | 0.0243 |

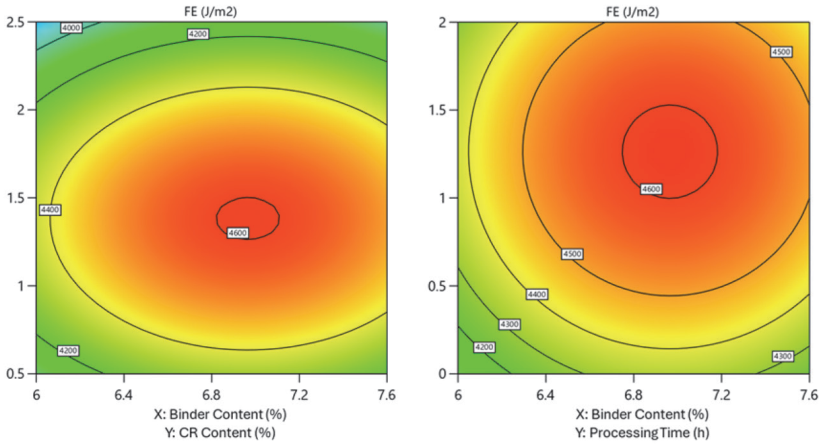


**Figure 1** The results of the response surface model for the fracture energy

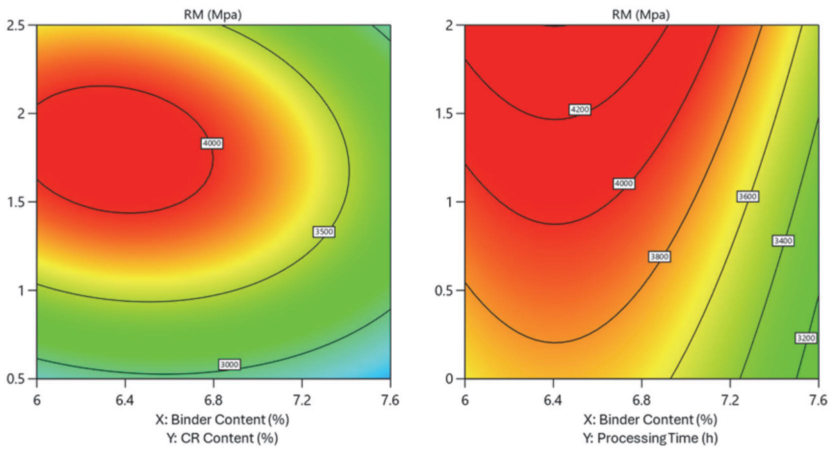


**Figure 2** The results of the response surface model for the resilient modulus

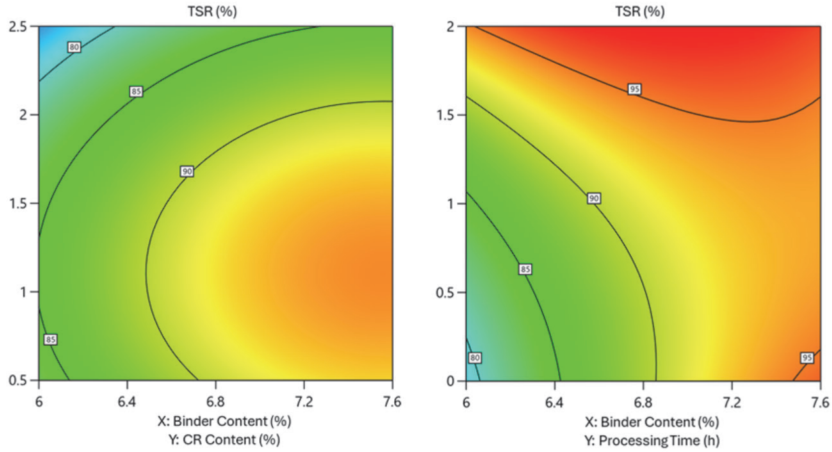


**Figure 3** The results of the response surface model for the tensile strength ratio

## 4 Conclusions

Conducting an in-depth investigation on the mechanical performance of rubberised Stone Mastic Asphalt (SMA), this study focuses on the key factors influencing its fracture energy, resilient modulus, and moisture susceptibility. Employing a dry process and using Response Surface Methodology (RSM) and statistical analysis, the experimental results revealed intricate interactions among independent variables, including CR content, bitumen content, processing time, and CR size. The study draws the following conclusions from the results:

- In FE and TSR, the bitumen content is the most influential factor, while in RM, CR size plays the key role in controlling performance.
- FE shows a distinctive response pattern in relation to bitumen content. Higher bitumen content, around 7%, results in a peak in FE. Beyond this threshold, a gradual decline is observed, suggesting a nuanced dependence on bitumen concentration for FE performance in CR-SMA mixtures.
- In the context of RM, CR size has a dominant role. The mixtures demonstrate robust resilience, particularly with higher CR content. The interplay of CR size, CR content, and bitumen content collectively shapes the internal structure, enhancing the overall stiffness and elastic recovery of the CR-SMA.
- With a binder content surpassing 7.0%, CR-SMA exhibits a consistent moisture performance, maintaining stability within the range of 90-95% despite prolonged processing times. The elevated binder content effectively mitigates the effects of short-term aging, ensuring sustained high moisture resistance in CR-SMA mixtures.
- The study reveals that processing time can have a more impact on CR-SMA performance, especially in combination with specific CR and bitumen levels.
- This study improves our knowledge of rubberised SMA mixture performance, laying the groundwork for creating more durable and sustainable CR-SMA mixtures. The trends and thresholds identified provide useful guidance for future construction, maintenance, and rehabilitation efforts, ensuring better performance of rubberised SMA pavements in real-world applications.

## References


[1] Mohajerani, A., Burnett, L., Smith, J.V., Markovski, S., Rodwell, G., Rahman, M.T., Kurmus, H., Mirzababaei, M., Arulrajah, A., Horpibulsuk, S., Maghool, F.: Recycling waste rubber tyres in construction materials and associated environmental considerations: A review, Resources, Conservation and Recycling, 155 (2020) 104679

[2] Zakerzadeh, M., Shahbodagh, B., Ng, J., Khalili, N.: The use of waste tyre rubber in Stone Mastic Asphalt mixtures: A critical review, Construction and Building Materials 418 (2024) 135420, DOI: 10.1016/j.conbuildmat.2024.135420

[3] Presti, D.L.: Recycled tyre rubber modified bitumens for road asphalt mixtures: A literature review, Construction and Building Materials, 49 (2013), pp. 863-881, DOI: 10.1016/j.conbuildmat.2013.09.007

[4] Nanjegowda, V.H., Biligiri, K.P.: Recyclability of rubber in asphalt roadway systems: A review of applied research and advancement in technology, Resources, Conservation and Recycling, 155 (2020) 104655, DOI: 10.1016/j.resconrec.2019.104655

[5] Navarro, F.J., Partal, P., Martınez-Boza, F., Gallegos, C.: Thermo-rheological behaviour and storage stability of ground tire rubber-modified bitumens, Fuel, 83 (2004) 14-15, pp. 2041-2049

[6] Hernández-Olivares, F., Witoszek-Schultz, B., Alonso-Fernández, M., Benito-Moro, C.: Rubber-modified hot-mix asphalt pavement by dry process, International Journal of Pavement Engineering, 10 (2009) 4, pp. 277-288

[7] Rahman, M.M., Airey, G.D., Collop, A.C.: Moisture susceptibility of high and low compaction dry process crumb rubber–modified asphalt mixtures, Transportation research record, 2180 (2010) 1, pp. 121-129

[8] Lastra-González, P., Calzada-Pérez, M.A., Castro-Fresno, D., Vega-Zamanillo, A., Indacoechea-Vega I.: Comparative analysis of the performance of asphalt concretes modified by dry way with polymeric waste, Construction and Building Materials, 112 (2016), pp. 1133-1140, DOI: 10.1016/J.CONBUILDMAT.2016.02.156

[9] Cao, W.: Study on properties of recycled tire rubber modified asphalt mixtures using dry process, Construction and building materials, 21 (2007) 5, pp. 1011-1015, DOI: 10.1016/j.conbuildmat.2006.02.004

[10] Farouk, A.I.B., Hassan, N.A., Mahmud, M.Z.H., Mirza, J., Jaya, R.P., Hainin, M.R., Yaacob, H., Yusoff, N.I.M.: Effects of mixture design variables on rubber–bitumen interaction: properties of dry mixed rubberized asphalt mixture, Materials and Structures 50 (2017), 1-10

[11] Putman, B.J., Amirkhanian, S.N.: Utilization of waste fibers in stone matrix asphalt mixtures, Resources, Conservation and Recycling, 42 (2004) 3, pp. 265-274

[12] Sharma, V., Goyal, S.: Comparative study of performance of natural fibres and crumb rubber modified stone matrix asphalt mixtures, Canadian Journal of Civil Engineering 33 (2006) 2, pp. 134-139

[13] Sarang, G., Lekha, B.M., Monisha, M., Shankar, A.U.R.: SMA mixtures with modified asphalt and treated aggregates, Second Transportation & Development Congress 2014, pp. 290-299, Orlando Florida, United States, 6-11 August 2014.

[14] Dias, J.L.F., Picado-Santos, L.G., Capitão, S.D.: Mechanical performance of dry process fine crumb rubber asphalt mixtures placed on the Portuguese road network, Construction and Building Materials. 73 (2014), pp. 247-254, DOI: 10.1016/j.conbuildmat.2014.09.110

[15] Xie, Z., Shen, J.: Performance properties of rubberized stone matrix asphalt mixtures produced through different processes, Construction and Building Materials, 104 (2016), pp. 230-234, DOI: 10.1016/j.conbuildmat.2015.12.063

[16] Shen, J., Li, B., Xie, Z.: Interaction between crumb rubber modifier (CRM) and asphalt binder in dry process, Construction and Building Materials, 149 (2017), pp. 202-206, DOI: 10.1016/j.conbuildmat.2017.04.191

[17] Huang, B., Mohammad, L.N., Graves, P.S., Abadie, C.: Louisiana experience with crumb rubber-modified hot-mix asphalt pavement, Transportation Research Record, 1789 (2002) 1, pp. 1-13

[18] Mashaan, N.S., Karim, M.R.: Evaluation of permanent deformation of CRM-reinforced SMA and its correlation with dynamic stiffness and dynamic creep, The Scientific World Journal, 2013, DOI: 10.1155/2013/981637

[19] Mashaan, N.S., Karim, M.R., Abdel Aziz, M., Ibrahim, M.R., Katman, H.Y., Koting, S.: Evaluation of fatigue life of CRM-reinforced SMA and its relationship to dynamic stiffness, The Scientific World Journal, 595 (2014), DOI: 10.1155/2014/968075