Analysis of Influence of the Dolomite Inactive Mineral Filler Quantity on Properties of Deep Cold Recycled Mixtures with Foamed Bitumen

Przemysław Buczynski 1, Marek Iwanski 1

1 Department of Transportation Engineering, Faculty of Civil Engineering and Architecture, Kielce University of Technology, al. Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland

Abstract. The subject of research presented in article was an assessment of the impact of inactive mineral filler content, i.e. dolomite dust, on the recycled cold mix properties with foamed bitumen. The analysis of the impact of dolomite mineral dust was made on the basis of the experiment design type 3^3. It consisted of three levels of foamed bitumen factor in the range from 1.2% to 3.6% with a 1.2% step and the amount of mineral dust factor in range from 5% to 20% with a 7.5% step. Dolomite dust is a waste material derived from aggregate mining. Foamed bitumen was obtained from foaming process of the neat bitumen 50/70 at water temperature of 25ºC and its amount of 2.7%. In order to increase the cohesion of the recycled cold mix with foamed bitumen, Portland cement CEM I 32.5 R in amount of 2.0% was used. The assessment of the impact of quantitative variables was carried out in accordance with the adopted plan of the experiment that assumed the determination of physical and mechanical properties such as: resistance to climatic factors, dynamic modulus (E*) and phase angle. Analysis of the test results shown that factors quantity affects the variability of analysed features. In the entire scope of experiment plan, the obtained free space values met the requirements in required guidelines. The highest sealing of the recycled mixture was observed for the entire dolomite dust dosage but at maximum amount of foamed bitumen amounted to 3.6%. It was also observed that the maximum water resistance (TSR) was obtained for mixtures with a minimum amount of mineral dust (5%) as well as the maximum amount of dust in the recycled cold mix (20%). However, it was depended of the amount of foamed asphalt in a recycled mixture composition. The study also was considered the influence of the amount of dolomite mineral dust on the change in stiffness modulus tested by means of IT-CY and DTC-CY procedure. It was shown that either stiffness modulus measured by IT-CY or DTC-CY are foam bitumen and dust amount dependent. To assess the rheological properties, the direct compression-compression test (DTC-CY) was used. All samples were subjected to a cyclic sinusoidal constant strain with an amplitude of εo<25με. The tests were carried out in the temperature range (-7ºC, 5ºC, 13ºC, 25ºC, 40ºC) and loading time (0.1 Hz, 0.3 Hz, 1 Hz, 3 Hz, 10 Hz, 20 Hz). It was found a significant variability of recycled base stiffness depending on loading time and temperature.
1. Introduction
Cold recycled road base mixtures with foamed bitumen (FB-RCM) may be an alternative to the traditional hot asphalt concrete road bases (HWMA). This is made possible by lowering the viscosity of the bituminous binder in the foaming process. The production of foamed bitumen is obtained by water foaming [1] and with zeolites [2]. Regardless of the medium in the foaming process, the primary function of foamed bitumen in FB-RCM is to combine all minerals. The aim is to obtain the proper recycled mixture cohesion. A similar phenomenon is observed in mineral-cement-emulsion mixtures, in which a bitumen emulsion is applied interchangeably to the foamed bitumen.[3]. In case of cold recycled mixtures with foamed bitumen it is required that the mineral mixture has a suitable part content of less than 0.063 mm[4] [5] [6]. Literature research [7] [8] [9] confirms that the bitumen foam combines with a fine-grained material to form a mastic. Therefore, the use of mineral dust in the composition of the cold recycled mixtures with foamed bitumen allows determining that their presence is essential for the high quality of a recycled mixture.

2. Design of experiments
An analysis was carried out according to the assumed algorithm of the design of experiments to explain the influence of the dolomite mineral dust and foamed bitumen quantity on studied properties of the cold recycled mixtures with foamed bitumen. All studied parameters of the recycled road base were evaluated on the basis of the 3x3 composition factorial design[10] [11]. They made up three percentages of foamed bitumen from 1.2% to 3.6% with a step of 1.2% and the amount of dolomite mineral dust from 5% to 20% with a step of 7.5%. The mineral dust percentage share and the amount of bituminous binder used in the design of experiments was adopted on the basis of the literature research [10] [12]. The field of experiment is shown in Figure 1.

3. Subject of Tests, Materials, Test Agenda
3.1. Subject of Tests
FB-RCM – recycled cold mixture with foamed bitumen was the subject of tests to assess the influence of the dolomite mineral dust quantity on the mixture properties. The mixture composition design was in line with the national guidelines for FB-RCM. [4]. In the composition of the recycled mineral mixture a variable proportion of dolomite inactive mineral filler was applied in the amounts of 5%, 12.5% and 20% respectively. The amount of dolomite mineral dust in the composition of the recycled...
mixture resulted from the adopted design of 3x3 factorial experiment. The designed grain size curves are shown in Figure 2.

![Figure 2. The grain-size curves of cold recycled mixtures with foamed bitumen](image)

3.2. Hydraulic binder and bitumen binder
To increase the cold recycled mixture cohesion, Portland cement (PC) of CEM I 42.5R class was used in the amount of 2.0%. Foam bitumen was produced from 50/70 road bitumen. The road bitumen properties are shown in Table 1 and the properties of Portland cement CEM I 42,5R in Table 2.

| Property                          | Research method | uom     | Result |
|----------------------------------|-----------------|---------|--------|
| Penetration at 25°C              | EN 1426         | 0.1 mm  | 59     |
| Softening point                  | EN 1427         | °C      | 49.5   |
| Breaking point (Fraass)          | EN 12593        | °C      | -13    |
| Kinematic viscosity at 135°C     | EN 12595        | mm²/s   | 488    |
| Dynamic viscosity at 60°C        | EN 12596        | Pa*s    | 290    |

Table 1. The properties of 50/70 road bitumen

| Property                          | Research method | uom     | Result |
|----------------------------------|-----------------|---------|--------|
| Components and composition:      |                 |         |        |
| - Portland clinker               | EN 196-3        | min     | 182    |
| - Secondary components           |                 |         |        |
| Setting time start               |                 |         |        |
| after 2 days                      | EN 196-1        | MPa     | 31.9   |
| after 28 days                     |                 | MPa     | 57.8   |
| Volume stability                  | EN 196-3        | mm      | 0.6    |
| Specific surface                  | EN 196-6        | cm²/g   | 4282   |

Table 2. Properties of Portland cement CEM I 42.5R

The use of 50/70 road bitumen was determined according to the design of experiments and to the methodology used by the authors of the paper [13]. The optimum moisture content required to obtain the bitumen foam was determined in accordance with the requirements of the guidelines [14] [4]. The bitumen foam was produced in the foamed bitumen plant. The assessment result is shown in Figure 3.
In case of cold recycled mixture, it is necessary to determine the optimum moisture content (OMC) for compacting samples. The optimum moisture content assessment was carried out in accordance with the requirements of the PN-EN 13286-2 standard [15] with to the Proctor test. The test result is shown in Figure 3.

Table 3. The optimum moisture content for cold recycled mixture for dolomite dust.

| Mixture               | Research method | uom | OMC |
|-----------------------|-----------------|-----|-----|
| FB-RCM MD-D=5%        |                 | 5.5 |     |
| FB-RCM MD-D=12.5%     | EN 13286-2      | 6.1 |     |
| FB-RCM MD-D=20%       |                 | 6.6 |     |

3.3. Dolomite mineral dust
Dolomite mineral dust was produced by aggregate dedusting process at the mine. The basic test results of dolomite mineral dust are presented in Table 4. The grain-size distribution analysis was carried out with laser diffraction[16].

Table 4. Basic properties of mineral dust

| Property                        | Symbol | uom   | Dolomite dusts (Dol) |
|---------------------------------|--------|-------|----------------------|
| Particle density                | $\rho$ | [g/cm$^3$] | 2.814               |
| Specific surface                | $P_w$  | [cm$^2$/g] | 26.729              |
| Voids, of dry compacted dust    | AVR    | [%]    | 36.0                 |
| Fine particle content.          | MB$_f$ | [-]   | 1.5                  |
| Reaction                        | pH     | [-]   | 8.1                  |
| Particle size distributions (µm)|        |       |                      |
| 63,0                            |        | 80.1  |
| 59,3                            |        | 24.6  |
| 42,1                            |        | 12.2  |
| 23,7                            |        | 4.2   |
| 15,9                            |        | 2.1   |

4. Test agenda and preparation of samples
4.1. Test agenda
Analysis of the influence of the dolomite dust quantity on properties of cold recycled mixtures with bitumen was performed according to the following design of experiments:

- Basic physical and mechanical properties:
Air void $V_m$ according to PN-EN 12697-8 [17].

- Resistance to weather:
  - Moisture resistance TSR according to Wirtgen 2006[6],

- Stiffness of cold recycled mixture:
  - unconfined compressive strength test at $+25^\circ \text{C}$ according to WT-5 2010 [18] and procedures related to the controlled strain speed range included in ASTM D2166 / D2166M - 16 Standard Test Method for Unconfined Compressive Strength of Cohesive Soil [19],
  - stiffness modulus testing in the indirect tensile test (IT-CY) at 13°C according to PN-EN 12697-26 appendix C [20],

- Rheological properties, i.e. dynamic modulus $|E^*|$
  - dynamic modulus test according to PN-EN 12697-26 appendix D [20].

4.2. Preparation of samples under laboratory conditions

Samples for testing basic physical and mechanical properties were compacted in a static press under 80 kN and the compaction time was 3 minutes [4] [21]. In case of rheological properties testing, the samples were compacted in a gyro press in accordance with the requirements of PN-EN 12697-31 standard [22]. The gyro press setting parameters were determined on the basis of literature research [23] [24] [25]. The number of compaction revolutions was selected individually for the mixtures to obtain the compactness at which the void content in the recycled mineral-cement mix with foamed bitumen was equal to $V_m=12.0\%$. The diameter of samples prepared for testing recycled mixture with foamed bitumen (FB-RCM) was D=150 mm and the height of H=180 mm.

5. Results and discussions

The main part concerning the analysis of influence of the quantity of mineral dust (Dust) and foamed bitumen (Bitumen) on the properties of the cold recycled mixture with foamed bitumen was the development of a regression mathematical model[10] [11]. The boundary conditions were determined by the field of experiment. To describe the obtained relationships, a second-degree polynomial (1) was applied, the form of which can be written as follows:

$$y = b_0 + b_1 \cdot x_1 + b_2 \cdot x_2 + b_3 \cdot x_2 \cdot x_1 + b_4 \cdot x_1^2 + b_5 \cdot x_2^2$$  \hspace{1cm} (1)

where:

- $b_0 \div b_5$ - value of experimental coefficients,
- $x_1$ - amount of mineral dust (Pył / Dust) [%]
- $x_2$ - amount of foamed bitumen (Asfalt / Bitumen) [%]

The significance of factors influencing the model was assessed in the second analysis stage. The significance assessment was performed for the assumed statistical significance of p-value<0.05.

5.1. The response surface model for physical and mechanical properties

The results of the regression model fitting for the analysed properties are presented in Figure 4. The significance assessment of factors influencing the model is presented in Table 5. The factors, the F statistics value of which is lower than the assumed statistical significance of p-value<0.05, were marked in grey.
Figure 4. Results for FB-RCM with dolomite dusts covering: a) void content $V_m$, b) moisture resistance TSR, c) unconfined compressive strength UCS, d) stiffness modulus in indirect tensile $S_m$.

Table 4. Response surface fitting parameters with the second-degree polynomial for cold recycled mixture with foamed bitumen and dolomite dusts

|        | Constant | (1)Dust, % (L) | Dust, % (Q) | (2)Bitumen, % (L) | Bitumen, % (Q) | IL wz.2L | MS      | $R^2$ |
|--------|----------|----------------|-------------|-------------------|----------------|-----------|---------|-------|
| $V_m$ [%] | 13.901   | -0.252         | 0.007       | -0.41             | -0.347         | 0.048     | 0.19    | 0.94  |
| TSR [%]  | 99.179   | -0.768         | 0.057       | -20.472           | 5.934          | -0.543    | 90.53   | 0.39  |
| UCS [MPa] | 8654.40  | 122.39         | -5.247      | -2565.48          | 569.123        | 11.32     | 55370.6 | 0.87  |
| $S_m$ [MPa] | 35211.09 | 398.35         | -10.0       | -23033.8          | 4788.08        | -96.528   | 867507.9 | 0.95  |

The second-degree polynomial was used to describe the obtained relationships. The determination factor $R^2$ was used to assess the quality of the mathematical models obtained. For characteristics: The obtained models $V_m$, UCS and $S_m$ describe the obtained relationships well as the value of $R^2$ coefficient...
is close to 0.9. Only in case of the TSR characteristic, the obtained model describes relationships in 39%.

Assessing the influence of the amount of dolomite mineral dust on the physical and mechanical properties of the cold recycled mixture with foamed bitumen (FB-RCM), it should be noted that the amount of mineral dust influences the change in the analysed properties to a different degree depending on the parameter type under consideration. In case of the void content, it was observed that the obtained void values were within the limits permitted by the guidelines [4]. The highest seal of the recycled mixture was observed for the dolomite mineral dust batching range from 5% to 20%, but with the maximum quantity of foamed bitumen of 3.6%. Inverse relationship, within the void content, was observed with a minimum quantity of foamed bitumen equal to 1.2%. Therefore, the use of mineral dusts in the composition of the recycled mixture generates the need to increase the amount of bitumen in order to reduce the void content ($V_m$). Increasing the mineral dust amount in the FB-RCM composition influences the increase in the specific surface of the mineral mixture and as a result it is necessary to increase the amount of foamed bitumen to obtain an appropriate thickness of the bitumen envelope on the aggregate [26]. The maximum moisture resistance (TSR) of the recycled mixture (FB-RCM) was achieved with a minimum quantity of mineral dust (5%) and its maximum quantity in the FB-RCM composition (20%), yet it depends on the amount of foamed bitumen in the recycled mixture. Therefore, the use of mineral dusts requires a thorough assessment of its impact in terms of climatic factors. Assessing mechanical properties: UCS, Sm it can be observed that the amount of mineral dust (Dust) and the amount of foamed bitumen (Bitumen) have a statistically significant effect on the analysed properties.

In case of the Sm stiffness property, a statistically significant effect ($\alpha \leq 0.05$) was also observed between the amount of bitumen and the amount of mineral dust.

5.2. The dynamic modulus test results $|E^*|$

The assessment of the influence of dolomite mineral dust on the dynamic modulus of the cold recycled mixture with foamed bitumen was performed in the direct tension-compression test on cylindrical samples [20] where the sample is subjected to cyclic sinusoidal load with low deformation from 25 to 50 $\mu$ε [20] [27]. The tests were performed at five temperature values (-10°C, 5°C, 13°C, 25°C, 40°C) and six loading times (0.1 Hz, 0.3 Hz, 1 Hz, 3 Hz, 10 Hz, 20 Hz). Lead curve models were developed on the basis of the obtained values of the dynamic modulus for the FB-RCM mixtures. The lead curve models were developed using the Richards model [28], which is a modification of the model presented in the NCHRP 9-29 report: PP 02 [29]. This methodology is also used by researchers to develop the dynamic modulus [30]. The presentation of the dynamic modulus lead curve uses the time-temperature superposition principle. To do so, it is necessary to enter the temperature displacement coefficient ($\alpha_T$) [27] implemented in the formula (2):

$$\log|E^*| = \delta + \frac{\alpha}{1 + \lambda e^{\beta + \gamma \log(a + b T + c T^2)}} T^{\lambda}$$

where:

- $|E^*|$ – dynamic modulus,
- $\omega$ – angular frequency,
- $\delta$ – lower asymptote value,
- $\alpha$ – difference between upper and lower asymptote value,
- $\lambda, \beta, \gamma$ – lead curve fitting parameter,
- $T$ – test temperature,
- $T_{ref}$ – reference temperature,
- $a, b, c$ – modulus temperature

The time and temperature superposition principle was applied to develop the lead curves of the composite module of cold recycled mixtures with foamed bitumen [29] [31]. For this purpose, the sigmoid function was optimized by minimizing the sum of the squared deviation for the determined composite modulus [32]. As a result of the function optimization, it was necessary to determine the lead curve parameters ($\alpha, \beta, \gamma, \delta, \lambda, a, b$). The evaluation of the parameters is presented in Table 5, while the composite modulus lead curves are shown in Figure 5.
Table 5. The lead curves fitting parameters of the E* composite modulus for FB-RMC.

| Mixtures         | Fitting parameters | Modulus [MPa] | Fit quality |
|------------------|--------------------|---------------|-------------|
|                  | a         | b        | α       | β      | γ      | δ   | λ   | E_∞   | E_0    | RRMSE [%] | R^2   |
| MD-D=5/A=1,2     | 2.60     | -0.011  | 2.73   | 0.31   | -0.06  | 2.73 | 0.1  | 532   | 283611 | 4.5       | 0.999 |
| MD-D=12.5/A=1,2  | 2.64     | -0.011  | 2.17   | 2.50   | -0.41  | 2.17 | 6.15 | 149   | 22246  | 0.67      | 0.963 |
| MD-D=20/A=1,2    | 2.81     | -0.009  | 2.18   | 1.97   | -0.29  | 2.18 | 2.09 | 151   | 22916  | 0.96      | 0.974 |
| MD-D=5/A=2.4     | 3.65     | -0.003  | 2.10   | 6.96   | -0.24  | 2.10 | 0.1  | 127   | 16251  | 2.65      | 0.982 |
| MD-D=12.5/A=2.4  | 3.45     | -0.004  | 2.08   | 5.04   | -0.23  | 2.08 | 0.1  | 119   | 14189  | 2.87      | 0.983 |
| MD-D=20/A=2.4    | 2.33     | -0.014  | 2.01   | 0.38   | -0.25  | 2.01 | 0.1  | 102   | 10411  | 2.39      | 0.9987 |
| MD-D=5/A=3.6     | 2.97     | -0.007  | 2.20   | 2.98   | -0.27  | 2.20 | 0.27 | 160   | 25724  | 1.26      | 0.997 |
| MD-D=12.5/A=3.6  | 2.66     | -0.011  | 2.20   | 1.07   | -0.23  | 2.20 | 0.1  | 159   | 25555  | 0.98      | 0.983 |
| MD-D=20/A=3.6    | 2.86     | -0.008  | 2.19   | 1.79   | -0.23  | 2.19 | 0.1  | 153   | 23667  | 1.64      | 0.973 |

Figure 5. The composite module lead curves at reference temperature T=25°C for cold recycled mixture with foamed bitumen and dolomite mineral dust

The analysis of the asymmetric sigmoid function mathematical model parameters fitting is characterized by high convergence of modulus values to the tested values. This proves that the course of functions was very well fitted to the tested values of the composite module shifted by the value of the αT factor. The accuracy assessment of the experimental data description by model data was based on the coefficient of determination R^2. It should also be added that the Relative Root Master Squared Error (RRMSE) values are insignificant (RRMSE < 1.0%) so the measurement results and the values obtained from the modulus are consistent with the experimental values and differ by up to 1%. The cement in the cold recycled mixture increases the dominance of the elastic component in the dynamic modulus |E*|. Similar relationships have been achieved by the authors in their works [33].

When analysing the dynamic modulus lead curves |E*| of the cold recycled mixture with foamed bitumen (FB-RCM), it should be noted that, both, the amount of mineral dust and the content of foamed bitumen influence the change of the dynamic modulus in terms of load time. The greatest variation in the dynamic modulus change was observed in the FB-RCM mixtures with 20% dolomite mineral dust content in the composition regardless of the load time. No significant changes were observed in the dynamic modulus value with a change in the amount of mineral dust in the FB-RCM mixtures containing 3.6% of foamed bitumen. The smallest dynamic modulus drop was observed in the lowest content of mineral dust and the lowest amount of foamed bitumen, i.e. for the FB-RCM mixture (MC-D=5/A=1.2).
6. Conclusions
Analysis of the test results leads to the following conclusions:

− increasing the mineral dust quantity in the FB-RCM composition influences the increase in the specific surface of the mineral mixture and as a result it is necessary to increase the quantity of foamed bitumen to obtain an appropriate thickness of the bitumen envelope on the aggregate,
− the use of mineral dust requires a detailed identification of their impact in terms of moisture resistance TSR,
− change in the amount of mineral dust in the FB-RCM mixtures containing 3.6% of foamed bitumen does not cause significant changes in the dynamic module value,
− maximum dynamic modulus values were observed in the mixtures with the amount of foamed bitumen equal to 1.2% in the entire range of mineral dust batching from 5% to 20%.

Acknowledgment(s)
The study results were developed within the framework of the project entitled “The use of recycled materials” under “RID” co-funded by the National Centre for Research and Development and the General Directorate for National Roads and Motorways in Poland.

References
[1] A. Chomicz-Kowalska, W. Gardziejczyk, i M. M. Iwański, „Analysis of IT-CY Stiffness Modulus of Foamed Bitumen Asphalt Concrete Compacted at 95°C”, Procedia Engineering, t. 172, s. 550–559, 2017.
[2] A. Woszuk, A. Zofka, L. Bandura, i W. Franus, „Effect of zeolite properties on asphalt foaming”, Construction and Building Materials, t. 139, s. 247–255, maj 2017.
[3] B. Dołzycki, M. Jaczewski, i C. Szydłowski, „The Impact of Long-Time Chemical Bonds in Mineral-Cement-Emulsion Mixtures on Stiffness Modulus”, The Baltic Journal of Road and Bridge Engineering, t. 13, nr 2, s. 121–126, cze. 2018.
[4] M. Iwański i in., „Procedury projektowania oraz wytyczne stosowania materiałów odpadowych i z recyklingu do technologii wytwarzania mieszanek metodą na zimno z asfaltem spięionym (MCAS)”. NCBiR, GDDKiA, Warszawa, 2018.
[5] P. Buczyński i M. Iwański, „Inactive Mineral Filler as a Stiffness Modulus Regulator in Foamed Bitumen-Modified Recycled Base Layers”, IOP Conference Series: Materials Science and Engineering, t. 245, s. 032042, paź. 2017.
[6] Wirtgen Group, „Podręcznik recyklingu na zimno”. Wirtgen GmbH, 2006.
[7] W. Ma, R. C. West, N. Tran, B. K. Diefenderfer, i C. Chen, „Effects of Mineral Additives on Cold Recycled Foamed Asphalt Mixtures Cured in Laboratory and Field Conditions”, Transportation Research Record: Journal of the Transportation Research Board, t. 2672, nr 26, s. 134–143, grudz. 2018.
[8] M. Iwański, P. Buczyński, i G. Mazurek, „The use of gabbro dust in the cold recycling of asphalt paving mixes with foamed bitumen”, Bulletin of the Polish Academy of Sciences Technical Sciences, t. 64, nr 4, s. 763–773, grudz. 2016.
[9] P. Fu, D. Jones, J. T. Harvey, i F. A. Halles, „Investigation of the Curing Mechanism of Foamed Asphalt Mixes Based on Micromechanics Principles”, Journal of Materials in Civil Engineering, t. 22, nr 1, s. 29–38, sty. 2010.
[10] G. E. P. Box, J. S. Hunter, i W. G. Hunter, Statistics for experimenters: design, innovation, and discovery, 2nd ed. Hoboken, N.J: Wiley-Interscience, 2005.
[11] D. C. Montgomery, Design and analysis of experiments, Eighth edition. Hoboken, NJ: John Wiley & Sons, Inc, 2013.
[12] B. Dołzycki, M. Jaczewski, i C. Szydłowski, „The long-term properties of mineral-cement-emulsion mixtures”, Construction and Building Materials, t. 156, s. 799–808, grudz. 2017.
[13] G. Martinez-Arguelles, F. Giustozzi, M. Crispino, i G. W. Flintsch, „Investigating physical and rheological properties of foamed bitumen”, *Construction and Building Materials*, t. 72, s. 423–433, grudz. 2014.

[14] Wirtgen, *Cold Recycling Technology*. 2012.

[15] PN-EN 13286-2:2010, „Mieszanki niezwiązane i związane hydraulicznie - Część 2: Metody badań laboratorium oraz gęstości na sucho i zawartości wody - Zagęszczanie metodą Proctora”.

[16] ISO 13320:2009, „Particle size analysis -- Laser diffraction methods”.

[17] PN-EN 12697-8:2010, „Mieszanki mineralno-asfaltowe -- Część 8: Oznaczanie zawartości wolnej przestrzeni”.

[18] WT-5, „Mieszanki związane spojwem hydraulicznym do dróg krajowych”. 2010.

[19] ASTM D2166 / D2166M, „16 Standard Test Method for Unconfined Compressive Strength of Cohesive Soil”.

[20] PN-EN 12697-26, „Mieszanki mineralno-asfaltowe -- Metody badań mieszank mineralno-asfaltowych na gorąco -- Część 26: Sztywność”.

[21] A. Chomicz-Kowalska i P. Ramięczek, „Comparative Evaluation and Modification of Laboratory Compaction Methods of Road Base Mixtures Manufactured in Low-emission CIR Technology with Foamed Bitumen and Bitumen Emulsion”, *Procedia Engineering*, t. 172, s. 560–569, 2017.

[22] PN-EN 12697-31 :2007, „Mieszanki mineralno-asfaltowe -- Metody badań mieszank mineralno-asfaltowych na gorąco -- Część 31: Próbki przygotowane w prasie żyratorowej”.

[23] C. Godenzoni, A. Graziani, i D. Perraton, „Complex modulus characterisation of cold-recycled mixtures with foamed bitumen and different contents of reclaimed asphalt”, *Road Materials and Pavement Design*, t. 18, nr 1, s. 130–150, sty. 2017.

[24] A. Grilli, A. Graziani, i M. Bocci, „Compactability and thermal sensitivity of cement–bitumen-treated materials”, *Road Materials and Pavement Design*, t. 13, nr 4, s. 599–617, grudz. 2012.

[25] Y. Kim i H. “David” Lee, „Development of Mix Design Procedure for Cold In-Place Recycling with Foamed Asphalt”, *Journal of Materials in Civil Engineering*, t. 18, nr 1, s. 116–124, luty 2006.

[26] J. Piłat i P. Radziszewski, *Nawierzchnie asfaltowe: podręcznik akademicki*. Warszawa: Wydawnictwo Komunikacji i Łączności, 2010.

[27] N. I. M. Yusoff, G. D. Airey, i M. R. Hainin, „Predictability of Complex Modulus Using Rheological Models”, *Asian Journal of Scientific Research*, t. 3, nr 1, s. 18–30, sty. 2010.

[28] G. Rowe i M. Sharrock, „Alternate Shift Factor Relationship for Describing Temperature Dependency of Viscoelastic Behavior of Asphalt Materials”, *Transportation Research Record: Journal of the Transportation Research Board*, t. 2207, s. 125–135, grudz. 2011.

[29] M. Witzczak i R. Root, „Summary of Complex Modulus Laboratory Test Procedures and Results”, *Fatigue and Dynamic Testing of Bituminous Mixtures*, V. Puzinauskas, Red. 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959: ASTM International, 1974, s. 67–67–28.

[30] M. Pszczola, M. Jaczewski, D. Rys, P. Jaskula, i C. Szydlowski, „Evaluation of Asphalt Mixture Low-Temperature Performance in Bending Beam Creep Test”, *Materials*, t. 11, nr 1, s. 100, sty. 2018.

[31] G. Mazurek i M. Iwański, „Modelling of Asphalt Concrete Stiffness in the Linear Viscoelastic Region”, *IOP Conference Series: Materials Science and Engineering*, t. 245, s. 032029, paź. 2017.

[32] G. M. Rowe, G. L. Baumgardner, W. Rossiter, T. Wallace, i S. W. Dean, „Evaluation of the Rheological Properties and Master Curve Development for Bituminous Binders Used in Roofing”, *Journal of ASTM International*, t. 4, nr 9, s. 101016, 2007.

[33] P. Buczynski i M. Iwanski, „Rheological properties of mineral-cement mix with foamed bitumen with the addition of redispersible polymer powder”, *IOP Conference Series: Materials Science and Engineering*, t. 471, s. 032013, luty 2019.