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# INVESTIGATION OF TERTIARY FLOW BEHAVIOR OF BITUMEN STABILISED MATERIALS WITH BITUMEN EMULSION

# WYKORZYSTANIE METODY FLOW NUMBER DO OCENY ODPORNOŚCI NA DEFORMACJE TRWAŁE MIESZANEK STABILIZOWANYCH EMULSJĄ ASFALTOWĄ

**STRESZCZENIE.** Recykling głęboki nawierzchni drogowych w technologii na zimno zyskuje coraz większą popularność, wpisując się w trendy zrównoważonego rozwoju w budownictwie. Mieszanki stabilizowane emulsją asfaltową (Bitumen Stabilised Materials — BSM), stosowane do wykonywania podbudów drogowych, zawierają destrukt asfaltowy, kruszywo doziarniające, wodę oraz środki wiążące: emulsję asfaltową lub asfalt spieniony oraz cement. W zakresie właściwości mechanicznych, mieszanki BSM wykazują właściwości charakteryzujące zarówno materiały ziarniste, jak i lepkosprężyste. Analiza źródeł literaturowych wskazuje, że aspekt lepkosprężystości mieszanek BSM nie został dotychczas wystarczająco zbadany. W artykule przedstawiono wyniki prac nad syntezą i adaptacją procedur badania pełzania dynamicznego, stosowanych do oceny odporności na deformacje trwałe mieszanek mineralno-asfaltowych, w celu przeprowadzenia oceny właściwości mieszanek BSM. Badania metodą Flow Number przeprowadzono na mieszankach BSM z 50% i 70% zawartością destruktu asfaltowego, ilością emulsji asfaltowej w zakresie 4,5%–6,4% oraz dodatkiem cementu na poziomie 1%. W celu wyznaczenia wartości parametru Flow Number analizowano przebieg krzywych skumulowanego odkształcenia trwałego przy zadanych warunkach obciążenia i temperatury. Dokonano oceny dopasowana modelu matematycznego Franckena do danych empirycznych. Przeprowadzone badania i analiza danych wykazały, że ustalenie parametrów badania dynamicznego pełzania Flow Number na potrzeby badań mieszanek BSM wymaga indywidualnego podejścia uwzględniającego skład i właściwości objętościowe tych mieszanek. Przy właściwie dobranych warunkach obciążenia i temperatury, możliwe jest przeprowadzenie oceny odporności na deformacje trwałe mieszanek BSM, stosując metody badawcze aplikowane do lepkosprężystych mieszanek mineralno-asfaltowych.

**SŁOWA KLUCZOWE:** Bitumen Stabilised Materials (BSM), Flow Number, deformacje trwałe, technologia recyklingu na zimno.

**ABSTRACT.** Cold recycling technology is gaining popularity as a sustainable way of rehabilitating existing asphalt pavements. Bitumen Stabilised Materials with bitumen emulsion (BSMs) are cold recycling mixtures (CRMs) that contain RAP, virgin aggregates, bitumen emulsion, water, and active filler and exhibit a combination of mechanical properties of both granular and viscoelastic materials. However, the BSMs' mechanical performance in terms of viscoelasticity remains insufficiently explored. This study aimed to synthesize and adapt dynamic creep test methods, commonly used for HMA mixes, for characterizing tertiary flow behavior of BSMs. Tests were conducted on BSM mixtures with 50% and 70% RAP content, bitumen emulsion amount in the 4.5%–6.4% range, and 1% cement addition. The designed BSM series were also differentiated in terms of volumetric properties. Permanent deformation (PD) response of Bitumen Stabilised Materials was evaluated based on the analysis of the accumulated permanent strain curves obtained in repeated load tests. The experimental data were fitted to the Francken model, using an originally developed Python calculation script, to determine the Flow Number (FN) values for BSMs under specified loading stress and testing temperature conditions. The study showed that the specification of the Flow Number dynamic creep test parameters for testing BSMs requires an individual approach depending on the composition and volumetric properties of the mixture. With appropriately selected test conditions, the permanent deformation of BSMs can be evaluated by means of fitting the accumulated permanent strain curve to the Francken model and estimating Flow Number values.

**KEYWORDS:** Bitumen Stabilised Materials, flow number, tertiary flow, permanent deformation, cold recycling mixtures.

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# 1. INTRODUCTION

Raising awareness of the sustainability issues in asphalt industry leads to an increased interest in the application of recycling technologies in construction, maintenance and rehabilitation of a road network [1, 2]. Considering the flexible pavement base courses' construction, cold recycling technology is one of the economically and environmentally beneficial alternatives to Hot Mix Asphalt (HMA), since it allows for considerable raw material and energy consumption savings. In the cold recycling process, up to 100% of virgin aggregates in the mixture can be substituted by Reclaimed Asphalt Pavement (RAP) – secondary material obtained during milling of deteriorated pavements – and due to the use of bitumen emulsion or foamed bitumen as a bituminous binder, no heating processes during cold recycling mixtures' (CRMs) production and paving are required [3–5].

Bitumen Stabilised Materials with bitumen emulsion (BSMs) are cold recycling mixtures that consist of RAP, virgin aggregates, bitumen emulsion, water and active filler (e.g. cement). The amount of residual bitumen in these mixtures is equal to approximately 3%, while the cement content is limited to 1% of the mixture mass. Thanks to such combination of binding agents, BSMs are characterized by higher flexibility, lower stiffness and lower tendency to shrinkage cracking compared to other cold recycling mixtures, such as bound cement-treated materials (CTMs) and cement-bitumen-treated materials (CBTMs) [6, 7]. In the process of emulsion breaking, bitumen disperses among the fines and selectively covers coarse aggregate particles, creating local bituminous bonds in the BSM mixture [8, 9]. Due to a specific, non-continuously bound nature, BSMs exhibit complex behaviour of both granular and viscoelastic materials, with distress mechanisms of either permanent deformation (PD) or fatigue cracking [10, 11].

Permanent deformation resistance of BSMs depends on various factors connected to the mix composition: RAP content and quality, aggregate gradation and fine particle content, residual bitumen content, presence of cementitious binders, moisture content, as well as specimen's curing time and conditions [12–14]. A considerable variety of BSMs' mechanical behaviour patterns can be also expected depending on the mixture's air void content [15].

Following the nonlinear elastic material approach, BSMs display increased cohesion and a maintained level of friction angle compared to the parent material, with permanent deformation being primary failure mode [8, 9, 16]. The permanent deformation behaviour of BSMs treated as unbound materials is commonly assessed in dynamic triaxial testing, which allows to capture the material's shear failure and perform modelling of the BSMs' permanent deformation response [17, 18]. Taking into account the stress dependency of the granular-type BSMs, the stress ratio-based parameters (such as Deviator Stress Ratio firstly proposed in 2000 by Jenkins [19]) are introduced to determine the rate of BSMs' strain accumulation during Repeated Load Permanent Deformation (RLPD) tests carried out in a triaxial set-up [16, 20]. Nevertheless, based on the current state of research, it can be stated that a comprehensive classification of BSMs on the basis of RLPD triaxial test results is challenging due to a strong dependence of the chosen Deviator Stress Ratio on the shear properties of individual mixtures [18].

On the contrary, BSMs' permanent deformation performance in terms of viscoelastic nature of these mixtures remains briefly addressed in the scientific literature. Single cases of the application of wheel tracking (WTT) and Flow Number (FN) tests for determination of the CRMs' and BSMs' permanent deformation response were reported [14, 21–24]. Since the commonly used FN dynamic creep testing methodologies are dedicated specifically to bound asphalt mixtures, the current research in the field of CRMs attempts to adjust the testing conditions to reliably capture the tertiary flow behaviour of BSMs which are expected to exhibit HMA-like, viscoelastic properties. It has been reported that the mix composition (RAP and BE content, binder type used), volumetric properties and curing time are among the key factors which determine the permanent deformation response of Bitumen Stabilised Materials [21–23]. Moreover, in the work of Kim and Lee, attention was drawn to the possibility of the introduction of dynamic creep tests in the CRMs' mix design process as a complementary assessment method to validate the optimum emulsion content in the case of the materials' field performance prediction.

Summarizing the literature review, it can be stated that the previous research can only be considered a first step toward a more profound understanding of the permanent deformation behaviour of BSMs considering their viscoelastic nature. Due to a limited number of available literature sources in this field, additional studies on the possibility of defining universal test conditions, allowing for the most reliable and accurate capture of the onset of tertiary flow for BSMs, are needed.

The study aimed to adapt the AASHTO T378 [25] dynamic creep and recovery testing methodology, commonly used for HMA and WMA mixes, for characterizing the tertiary flow behavior of Bitumen Stabilised Materials with bitumen emulsion. The synthesis of testing conditions presented in the international standards and current research programs with respect to loading stress levels and the temperature was performed.

Two series of BSM mixtures differentiated in terms of RAP content, type and content of virgin aggregate, bitumen emulsion content and air void content were tested. Based on the obtained repeated load test results, the data fitting to the Francken model was performed to determine the Flow Number values for the designed mixtures and the analysis of accumulated permanent strain curves was carried out.

## 2. MATERIALS

Tests were conducted for two series of BSM mixtures containing 50% and 70% RAP 0/31.5 mm, derived from milling of wearing and base asphalt courses. The following mixtures' nomenclature was adopted: "BSM*X*_*Y*R", where *X* represents the BSM series' number: *X* = [1, 2] and *Y* – RAP content: *Y* = [50, 70]. In series 1, continuously graded dolomite aggregate 0/31.5 mm, continuously graded limestone aggregate 0/4 mm and limestone filler were used as virgin aggregates (VA), while in series 2, continuously graded basalt aggregate 0/31.5 mm and fine basalt aggregate 0/2 mm were added to meet the target grading criteria presented in the Wirtgen Cold Recycling manual [8]. According to the BSM mix design recommendations, RAP and VA particles retained on the 22.4 mm sieve were discarded. Grading curves for the designed BSM mixtures with target grading are shown in Fig.1. Properties of the RAP binder incorporated in the BSM mixtures are presented in Table1.

Table 1. RAP binder properties

| Property | Unit | Average value |
|---|---|---|
| RAP binder content | [%] | 4.5 (± 0.3) |
| RAP binder – penetration at 25°C | [0.1 mm] | 16 (± 1) |
| RAP binder – softening point | [°C] | 68.8 (± 1.8) |

Since the processing temperatures applied in cold recycling technology are significantly lower than those required to soften the severely aged binder present in RAP particles, the amount of RAP binder is not included in the determination of the total bitumen content in BSMs, according to the general practice in the CRMs mix design worldwide [8, 9, 26–28]. Therefore, in this work, the RAP material was treated as inactive and incorporated as a "black rock" aggregate into the designed mixtures.

Optimum bitumen emulsion (BE) contents applied in BSM1 and BSM2 mixtures, determined following the Wirtgen mix design procedure [8], are presented in Table 2. Cationic slow-setting bitumen emulsion type C60 B10 ZM/R, which met the requirements of the PN-EN 13808 standard [29], was used in the mixtures' preparation. The average bitumen content in the bitumen emulsion was equal to 58.4%.

The cement content was the same for all mixtures and limited to 1.0%. The optimum fluid content (OFC) for mixtures was determined following the modified Proctor moisture-density relationship procedure. The amount of water to be added in each of the mixes was calculated in accordance with national mineral-cement-emulsion mixtures' design guideline [28]. The designed mixtures varied in terms of air void content – the average air void content ranges were approximated as 18%–20% and 10%–12% for BSM1 and BSM2 series, respectively.

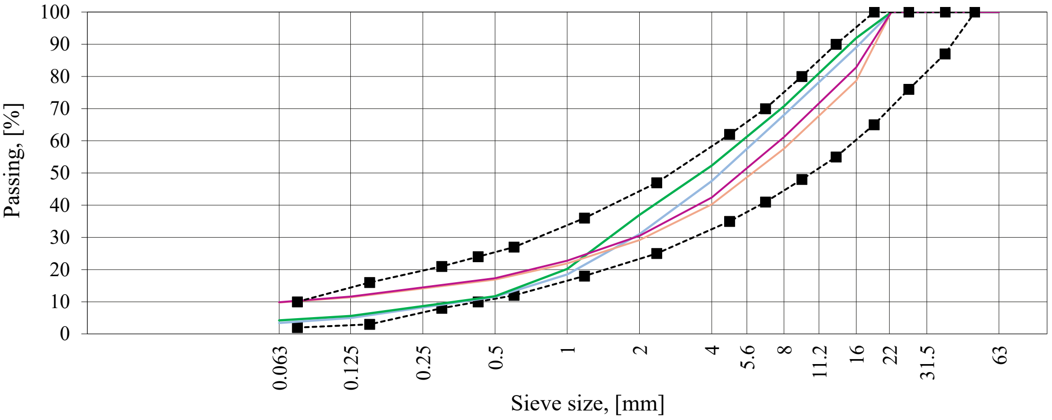

Fig. 1. BSM grading curves

Table 2. Optimum bitumen emulsion contents for the designed BSM mixtures

| BSM mixture designation | BE content [%] | Air void content (Vm) [%] |
|---|---|---|
| BSM1_50R | 5.2 | 19.3 (± 0.6) |
| BSM1_70R | 4.5 | 18.7 (± 0.4) |
| BSM2_50R | 6.4 | 11.2 (± 0.4) |
| BSM2_70R | 6.0 | 10.9 (± 0.5) |

## 3. TESTING METHODOLOGY

### 3.1. FLOW NUMBER METHOD

To evaluate BSMs' tertiary flow characteristics, the principles of the Flow Number test presented in the AASHTO T378 [25] standard were adopted. Since the analyzed testing methodology was primarily developed for hot and warm mix asphalt under the NCHRP 9–19 and NCHRP 9–29 projects, the aim of this work was to select suitable FN test parameters – loading stress level and temperature – to obtain reliable data on the primary, secondary and tertiary PD zones of the designed BSM mixtures', thus enabling a wider application of this method to assess the materials' permanent deformation response.

Dynamic creep and recovery tests were performed using the Asphalt Mixture Performance Tester (AMPT) device in stress-controlled mode under unconfined conditions. Specimens were subjected to repeated cycles of 0.1 s haversine pulse load and 0.9 s recovery period (f = 1 Hz). Accumulated permanent strain as a function of the number of load cycles was recorded. The Flow Number parameter, defined as the load cycle number at which the shear deformation under constant volume starts [30–33], was used to assess the BSMs' permanent deformation susceptibility.

Figure 2 presents a typical dynamic creep test result relationship with the three-staged permanent strain response and a graphic interpretation of the FN value.

Flow Number testing was carried out on a minimum number of 3 samples per mixture as required in the original HMA research methodology [25]. Specimens of 150 mm height and 100 mm diameter were cored and sawed from the cylindrical specimens (d = 150 mm, h = 170 mm) prepared in a gyratory compactor, which were previously subjected to an accelerated curing procedure – drying in an oven at 40°C for a minimum of 3 days, until reaching constant mass.

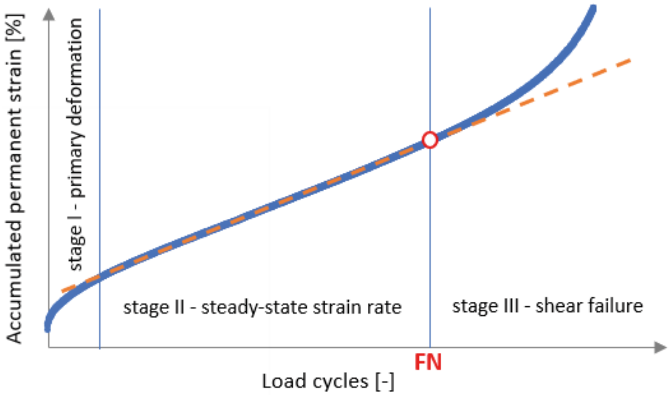

Fig. 2. Typical relationship between permanent strain and number of cycles in dynamic creep test city; and (e) $I_{B/S}$

Testing temperature selection was performed based on the conditions commonly applied in HMA permanent deformation resistance testing. Therefore, temperatures of 40°C (used in mastic asphalt static indentation test) and 60°C (as for Wheel Track Testing) were chosen. A similar range of test temperatures was adopted in the works of Kim & Lee, Silva, and Li [22–24], which concerned the Flow Number testing of CRMs.

The constant loading stress values of 400 kPa and 600 kPa were applied for tests carried out at both selected temperatures. Additionally, low loading stress levels of 140 kPa and 200 kPa were adopted in tests carried out at 40°C and 60°C, respectively. The value of 400 kPa was selected as an intermediate load level. Loading stress level of 600 kPa was chosen according to the AASHTO T378 standard recommendations for HMA, while the values of 140 kPa and 200 kPa were adapted from the research programs presented in the works of Kim & Lee and Silva et al. [22, 23].

Following the Flow Number testing research experience [23, 30, 31, 33], 10 000 load cycles were considered a maximum, reasonable test duration. Since the total testing time depends on the adopted test temperature and the loading stress level [22, 23], the possibility of capturing the onset of the tertiary stage within the limited number of cycles was selected as a criterion for assessing the suitability of the applied testing conditions for BSMs.

Detailed summary of the selected standard FN testing conditions for hot mix asphalt and proposed conditions for Bitumen Stabilised Materials is presented in Table 3.

Table 3. Summary of the selected Flow Number testing conditions for HMA and BSMs

| | **Standard conditions for Hot Mix Asphalt (HMA) [25]** | **Proposed conditions for Bitumen Stabilised Materials (BSM)** |
|---|---|---|
| Sample conditioning | Short-term conditioning of the mixture:<br>4h±5 min at (135±3)°C.<br>Sample pre-test conditioning typically of 4h at test temperature | No mixture conditioning.<br>Sample pre-test 4h conditioning at test temperature |
| Target air void content | (7±0.5)% | Air void content within the range of relevant CRM requirements |
| Test temperature | Adjusted PG temperature | 40°C, 60°C |
| Repeated axial stress level | 600 kPa | 140 kPa, 400 kPa, 600 kPa at 40°C<br>200 kPa, 400 kPa, 600 kPa at 60°C |
| Confining stress | 0 kPa (unconfined tests) | 0 kPa (unconfined tests) |
| Identification of the FN | Smooth central difference algorithm/Francken model | |
| Minimum average FN requirement | HMA: 50 – 740 cycles | Minimum average FN value to be verified |

## 3.2. FN ESTIMATION METHOD

Flow Number test data were fitted to the Francken model consisting of a power part and an exponential component, which accurately represents all three stages of the accumulated permanent strain curve, including the tertiary stage [30]. The Francken mathematical model is described as follows (Equation 1) [34]:

$$\varepsilon_p(N) = AN^B + C\left(e^{DN} - 1\right), \tag{1}$$

$\varepsilon_p(N)$ – permanent strain,
$N$ – number of loading cycles,
$A, B, C, D$ – regression coefficients.

Regression coefficients were determined using a Python programming language script with the use of statistical analysis and visualization packages (e.g. SciPy, NumPy, Pandas, Matplotlib), which was originally developed by the authors. The goodness of fit of the Francken model curve to the experimental data was quantitatively evaluated based on the statistical R-squared ($R^2$) value. At the same time, the qualitative assessment was carried out using QQ plots, with theoretical quantiles calculated based on the data sample residuals (i.e., the differences between the observed data points and the corresponding predictions made by the Francken model). The fitting accuracy was considered sufficient when the $R^2$ was more or equal to 0.70. In the case of the QQ plot, data points aligning along a straight 45° line suggest the normal distribution of the residuals, which indicates that the Francken model effectively captures the underlying patterns and variations in the experimental data.

The Flow Number value is defined as the cycle number corresponding to the minimum rate of the permanent axial strain change, calculated as a minimum value of the first derivative of the Francken function (Equation 2) [30, 33, 34]:

$$\varepsilon_p(N) = \frac{d\varepsilon_p(N)}{dN}. \tag{2}$$

The data analysis procedure is presented in Fig. 3.

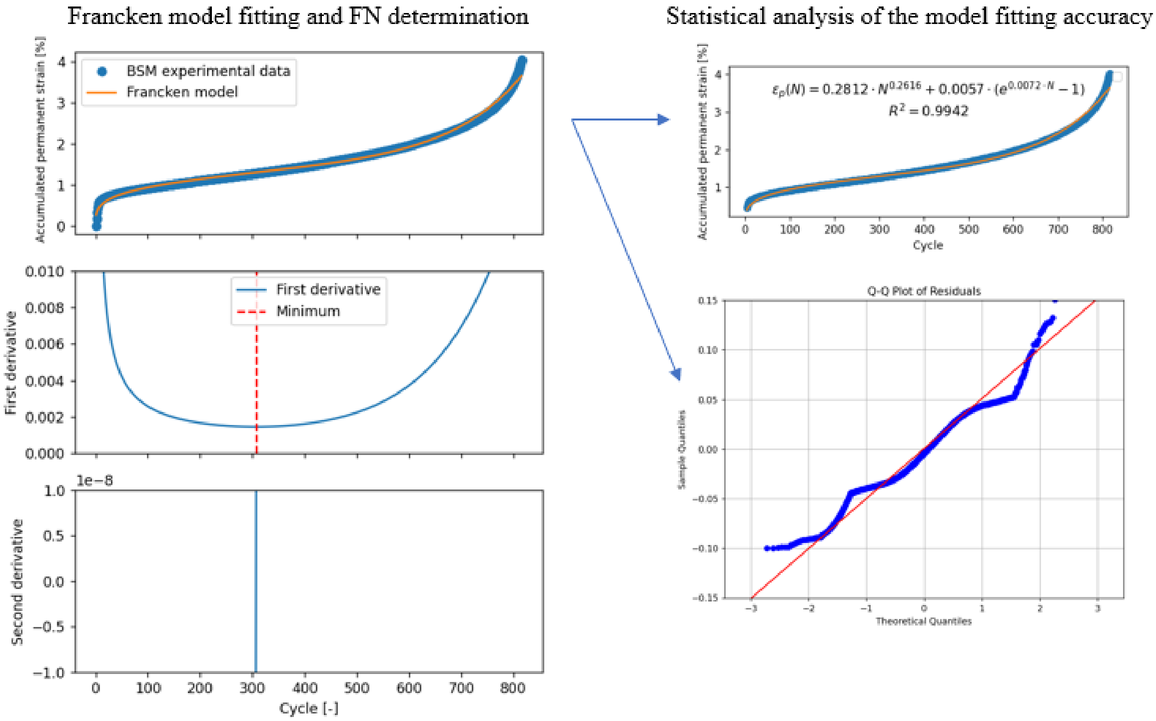

Fig. 3. FN testing data analysis procedure

## 4. RESULTS AND DISCUSSION

Results of Flow Number tests carried out at temperatures of 40°C and 60°C are presented in Table 4 and Table 5, respectively. The statistical analysis of the data was performed based on average FN values and the coefficient of variation (COV), which is a statistical measure of the relative dispersion of data points in a data series around the mean. COV parameter was defined as a ratio between the standard deviation and the average FN value in order to provide a reliable assessment of the test results.

Based on the results of FN testing performed with the lowest loading stress levels (i.e., 140 kPa and 200 kPa), it can be stated that, in general, BSM mixtures did not reach the Flow Number within the limited number of load cycles (*No FN* result), independently of the mix composition (RAP content), air voids content and applied test temperature. The only exception was the BSM1_70R composition, for which an average Flow Number of 7252 cycles was obtained in tests carried out at 60°C and with a 200 kPa loading stress. Fig. 4 presents representative permanent strain curves obtained in Flow Number tests with low loading stress conditions.

It should also be noted that for the BSM1_70R mix composition, one of the highest values of COV was observed, indicating high variability of the obtained results. However, determined COV values may be related not only to the material parameters, but also to specific test conditions. The $R^2$ values calculated in the Francken model data fitting process exceeded 90% for all tested BSM mixtures, primarily indicating satisfactory goodness of fit. However, based on the additional qualitative assessment using QQ plots, the residual plots for BSM mixtures with accumulated permanent strain curves characterized by a prolonged secondary stage deviated from the linear course. That implies that the data fitting accuracy may not be sufficient, with scattering between the experimental and theoretical values determined using the model. Such behaviour of the BSM mixtures is expected when the applied loading stress levels and/or testing temperature are inadequate (too low), resulting in high FN values (>7000 cycles in the case of BSMs tested in this work). Therefore, based on the obtained results, it can be concluded that the FN testing conditions considering low loading stresses (40°C and 140 kPa, 60°C and 200 kPa) are not recommended to be adopted in BSM tertiary flow testing. Observations made in this study are consistent with the conclusions presented

Table 4. Flow Number test results – temperature 40°C

| Mixture designation | Loading stress level [kPa] | | | | | |
|---|---|---|---|---|---|---|
| | 140 kPa | | 400 kPa | | 600 kPa | |
| | Average [-] | COV [%] | Average [-] | COV [%] | Average [-] | COV [%] |
| BSM1_50R | No FN* | - | 4165 | 12.1 | 57 | 14.1 |
| BSM1_70R | No FN* | - | 2818 | 10.3 | 22 | 16.9 |
| BSM2_50R | No FN* | - | No FN* | - | 2183 | 6.5 |
| BSM2_70R | No FN* | - | No FN* | - | 1732 | 7.3 |

* - specimens did not reach the tertiary flow point (Flow Number) within 10 000 load cycles

Tab. 5. Flow Number test results – temperature 60°C

| Mixture designation | Loading stress level [kPa] | | | | | |
|---|---|---|---|---|---|---|
| | 200 kPa | | 400 kPa | | 600 kPa | |
| | Average [-] | COV [%] | Average [-] | COV [%] | Average [-] | COV [%] |
| BSM1_50R | No FN* | - | 651 | 10.1 | 21 | 12.7 |
| BSM1_70R | 7252 | 20.3 | 290 | 8.0 | 9** | 42.1 |
| BSM2_50R | No FN* | - | 1753 | 9.2 | 497 | 7.7 |
| BSM2_70R | No FN* | - | 979 | 7.0 | 223 | 5.6 |

* - specimens did not reach the tertiary flow point (Flow Number) within 10 000 load cycles

** - average FN value estimated based on the smooth central difference algorithm due to a short test duration

in the work of Silva [23]. The researchers confirmed the low efficiency of the method proposed by Kim & Lee [22] in BSM Flow Number testing, with most specimens withstanding the loading stress of 140 kPa and the temperature of 40°C proposed by the method.

When an intermediate loading stress level (400 kPa) was applied in testing, it was observed that the mixture's volumetric properties significantly influenced the FN values. Analyzing test results obtained at a temperature of 40°C and the group of BSM mixtures containing 50% RAP, it was observed that BSM1_50R mixture with an 18%–20% air void content displayed shear failure at an average FN value equal to 4165 cycles. In contrast, the BSM2_50R mixture, characterized by a more dense structure, did not exhibit the onset of a tertiary PD stage within the limited test duration. The same tendency was observed in the case of BSM mixtures with 70% RAP. The observed phenomenon is most likely a result of different internal structure and cohesive properties of the mixture groups. It can be assumed that in the analyzed testing conditions, BSM1 mixtures exhibited lower cohesion, defined as structural integrity and behaviour resembling granular materials, due to the higher air void content and lower bitumen emulsion content than BSM2 mixes. Considering the mechanism and factors influencing the formation of non-continuous bitumen bonds in BSMs, the low amount of fines (3.8%–4.2%) at high air void content in BSM1 mixtures could affect the share of residual bitumen-aggregate contact zones developed in the mix skeleton, making the material more prone to permanent deformation.

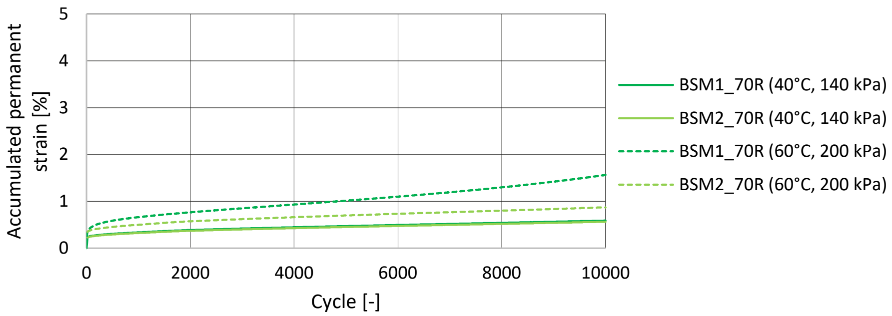

Fig. 4. Selected Flow Number test results for BSM mixtures with 70% RAP (low loading stress conditions)

Comparing FN values obtained at 40°C temperature and 400 kPa loading stress within the BSM1 mixture group, it can be found that the BSMs' mix composition had a significant influence on the permanent deformation response of the material – a 32% decrease in the average FN value for BSM1 mixture containing 70% RAP was observed, compared to BSM1_50R mixture with an equal share of RAP and virgin aggregates (VA) in mineral mixture. The reasons for this phenomenon can be sought in RAP and VA's different mechanical and physical properties. Higher compressive strength and angularity of VA particles compared to RAP containing aged bitumen binder can contribute to an increased resistance to permanent deformation of mixtures with a higher virgin aggregate share. On the other hand, the observed changes in permanent deformation response may be connected to the potential changes in the stiffness of the aged asphalt matrix in RAP occurring at 40°C, with such influence being more evident with an increase in RAP content in the mixture.

While maintaining the loading stress level at 400 kPa, increasing the temperature to 60°C contributed to an increased permanent deformation susceptibility of BSM mixtures, resulting in the reduction of the FN values for BSM1 series mixtures and obtaining representative FN results for the BSM2 series mixtures (Fig. 5). In the case of BSM1 mixtures, changes in the FN values for mixtures containing different amounts of RAP were quantified. For the BSM1_50R mixture, the average FN value determined at 60°C decreased by approximately 84% compared to FN at 40°C, while the BSM1_70R mixture showed a 10-fold difference in analogous values, indicating its higher thermal sensitivity compared to mixture with 50% RAP content (Fig.6). In the case of the BSM2 series, the mixture characterized by a 70% RAP amount displayed lower resistance to permanent deformation compared to the BSM2_50R mixture with an average FN value lower by 44%, which confirms the tendency observed for BSM1 mixtures tested at 40°C.

Analyzing the FN test results obtained at high loading stress levels (600 kPa), it can be stated that such conditions are more suitable for testing BSM mixtures with dense internal structure – lower air voids content and high fine particle share. In the case of the BSM2 series, the applied testing temperatures significantly differentiated the permanent deformation response of the material. With an increase in test temperature from 40°C to 60°C, the average FN value for the BSM2_50R mixture decreased by 77%, whereas for the BSM2_70R variant by 87%, implying higher temperature sensitivity of mixtures with an increased RAP content. Moreover, BSM2_70R displayed lower resistance to permanent deformation than BSM2_50R at corresponding test temperatures (Fig. 7). The observed trends are consistent with the behavior presented by the BSM1 series mixtures at a 400 kPa load.

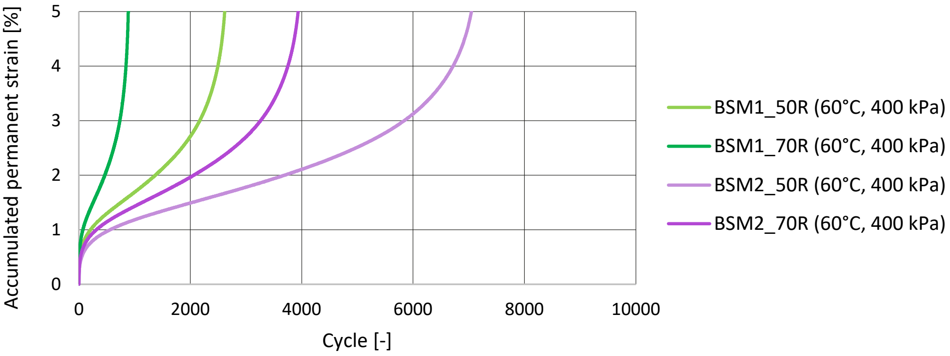

Fig. 5. Selected Flow Number test results for BSM mixtures tested at 60°C and 400 kPa loading level

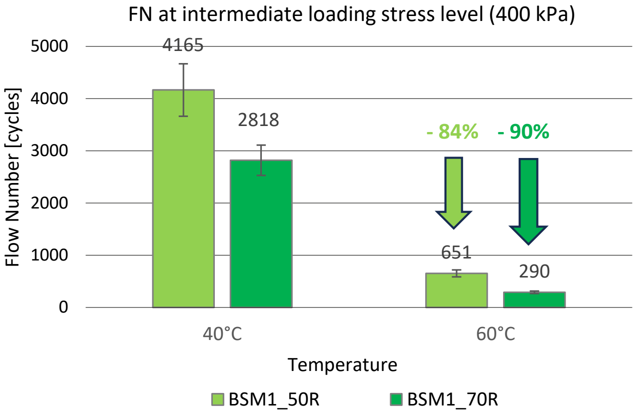

Fig. 6. Comparison of average FN values for BSM1 mixtures tested at 40°C and 60°C (400 kPa)

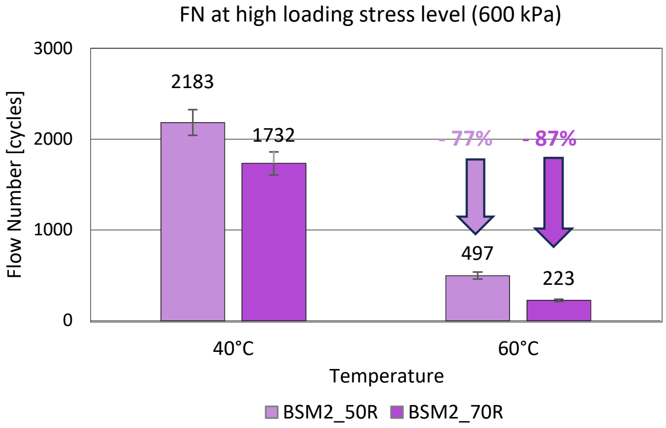

Fig. 7. Comparison of average FN values for BSM2 mixtures tested at 40°C and 60°C (600 kPa)

Considering the case of BSM1 mixture series with air void content ranging from 18% to 20%, subjecting specimens to high-stress levels resulted in significantly lower FN values

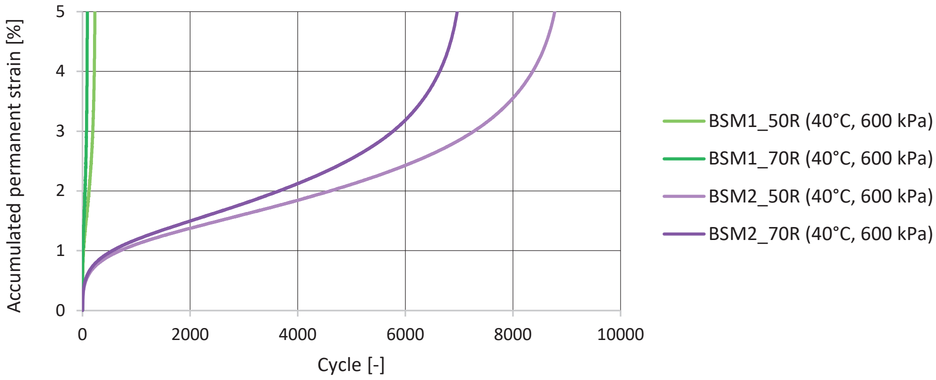

Fig. 8. Selected Flow Number test results for BSM mixtures tested at 40°C and 600 kPa loading level

(FN < 60 at both testing temperatures). In the extreme case of the BSM1_70R mixture, specimens' instant shear failure was observed, resulting in an estimated average FN number of 9 with a high COV (42.1%), indicating considerable data variability. Based on the obtained results, it can be stated that the evaluation of FN based on the accumulated strain curves characterized by a highly limited secondary stage of a steady-state strain increase is, in the case of non-continuously bound BSM mixtures, subject to a high risk of obtaining unreliable FN results due to quick failure of the specimen. Selected Flow Number test results for BSM1 and BSM2 mixtures tested at 40°C and 600 kPa loading stress are presented in Fig. 8.

Taking into account the obtained FN values at all testing temperatures and loading stress levels, it can be concluded that a reliable evaluation of the permanent deformation response of Bitumen Stabilised Materials is possible only with appropriately selected test conditions, taking into account the properties of tested BSMs.

## 5. CONCLUSIONS

In this paper, the Flow Number AASHTO T378-22 method was adapted for evaluating the tertiary flow behaviour of Bitumen Stabilised Materials, and its application was positively verified. It was observed that the permanent deformation characteristics of BSMs evaluated in FN tests depend on the applied loading stress level and temperature. Selection of the FN test parameters requires an individual approach depending on the properties of the BSM mixture, as the BSM mixture composition and air void content highly influenced the obtained FN values for specific test conditions.

Based on the results obtained in this study, the following detailed conclusions can be drawn:

- Low loading stress levels (i.e., 140 kPa and 200 kPa) did not allow for estimation of FN for tested BSM mixtures, independently of the mix composition (RAP and virgin aggregate content), air voids content, and applied test temperature.
- At an intermediate loading stress level (400 kPa), the volumetric properties of BSM mixtures significantly influenced the obtained FN values. At the temperature of 40°C, BSM1 mixtures with an air void content of 18%–20% exhibited shear failure at 4165 and 2818 cycles, while BSM2 mixtures with a dense structure (Vm = 10%–12%) did not exhibit the onset of the tertiary PD stage within the test duration.
- Increasing the temperature to 60°C at the 400 kPa stress level contributed to an increased permanent deformation susceptibility of BSM mixtures, reducing FN values for BSM1 series mixtures and obtaining representative FN results for the BSM2 series mixtures.
- High loading stress conditions (600 kPa) are more suitable for testing BSM mixtures with dense internal structure (low air voids content, high amount of fines). Applying high stresses (especially at high testing temperatures: 60°C) to mixtures with high air void content leads to a premature shear failure of the samples.
- BSM1 and BSM2 mixtures containing 50% RAP exhibited higher FN values indicating lower susceptibility to permanent deformation than mixtures with a higher RAP amount (70%) in comparable test conditions.
- Different temperature sensitivity was observed for BSM1 and BSM2 mixtures depending on the RAP content. At constant loading stress (400 kPa or 600 kPa), increasing test temperature caused a greater percentage decrease in the average FN value for mixtures containing 70% RAP than those with lower RAP content.

Conclusions on the permanent deformation performance of BSM mixtures with bitumen emulsion presented in this work need to be confirmed with further testing. A more complex investigation of changes in the BSMs' temperature sensitivity and permanent deformation susceptibility in terms of RAP content differentiation is crucial to provide insight into the BSMs' mechanical behaviour. Moreover, the analysis of other Flow Number testing parameters connected to the permanent deformation response of the individual material, i.e., accumulated permanent strain at FN, is recommended, especially when a wide range of RAP content is to be applied in the BSM mix design process.

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