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Rehabilitation reliability of the road pavement structure with recycled base course with foamed bitumen

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Abstract. This article presents a new approach to reliability assessment of the road structure in which the base layer will be constructed in the process of cold deep recycling with foamed bitumen. In order to properly assess the reliability of the structure with the recycled base, it is necessary to determine the distribution of stress and strain in typical pavement layer systems. The true stress and strain values were established for particular structural layers using the complex modulus (E*) determined based on the master curves. The complex modulus was determined by the direct tension-compression test on cylindrical specimens (DTC-CY) at five temperatures (-7ºC, 5ºC, 13ºC, 25ºC, 40ºC) and six loading times (0.1 Hz, 0.3 Hz, 1 Hz, 3 Hz, 10 Hz, 20 Hz) in accordance with EN 12697-26 in the linear viscoelasticity (LVE) range for small strains ranging from 25 to 50 με. The master curves of the complex modulus were constructed using the Richards model for the mixtures typically incorporated in structural layers, i.e., SMA11, AC16W, AC22P and MCAS. The values of the modulus characterizing particular layers were determined with temperature distribution in the structure taken into account, when the surface temperature was 40°C. The stress distribution was established for those calculation models. The stress values were used to evaluate the fatigue life under controlled stress conditions (IT-FT). This evaluation, with the controlled stress corresponding to that in the structure, facilitated the quality assessment of the rehabilitated recycled base course. Results showed that the recycled base mixtures having the indirect tensile strength (ITSDRY) similar to the stress in the structure under analysis needed an additional fatigue life evaluation in the indirect tensile test ITT. This approach to the recycled base quality assessment will allow eliminating the damage induced by overloading.

1. Introduction

Cold deep recycling with foamed bitumen [1, 2] and bitumen emulsion [3] is widely used for road rehabilitation in Poland and elsewhere. This technology helps eliminate the effects of fatigue life losses in the entire pavement layer system and restores the required service parameters of the structure [4]. A comparison of the recycled base to that constructed using conventional technologies, i.e., a base layer with unbound aggregate and cement concrete, shows a considerable advantage of cold recycling [5, 6, 7] in that it provides better cohesion relative to unbound mixture bases and lower stiffness relative to cement concrete bases. Hence, the cold recycled base layer with foamed bitumen (MCAS) contributes to the improved quality and reliability of the rehabilitated road pavement structure. Reliability of the structure is defined as its ability to satisfy the design life requirements.

The selection of rehabilitation technique requires a correct assessment of the existing surface condition [8]. In the case of structural strengthening, it is necessary to calculate fatigue life with regard
to material constants (stiffness modulus) for new layers. True values of material constants applied in the calculations will provide more accurate determination of the fatigue life of the rehabilitated road pavement [9]. To determine the stiffness modulus for describing the material used in the structural layers, specialized testing is necessary.

The specialized testing mentioned above was conducted by the authors of [10] for assessing the properties of a mineral-cement mixture with a bitumen emulsion for use in the base layer. The test results for the properties of the MCE mixture in terms of the curing period, 28 days and 18 months, provide information on changes in the stiffness modulus over time and can be taken into account in the design of the structure. The aspect of dosing synthetic fibres to the bituminous mixture was discussed in [11]. Temperature aspects and the effects of various additives used in the bituminous mixture were discussed extensively in [12, 13].

Nevertheless, the design that employs standard parameters alone fails to take advantage of the information about fatigue characteristics that vary between materials intended for the same layer. It is thus advisable to evaluate the quality of structural layers using the fatigue life test under cyclic load (controlled stress or strain). These issues have been described and discussed by many researchers [14-16]. As shown in [17], the addition of 35% reclaimed asphalt pavement (RAP) material to the hot mix asphalt (HMA) mixtures required the assessment of fatigue life to confirm that 35% RAP content would not cause the fatigue life loss. The addition of 30% RAP in combination with a bio-agent improved the fatigue life [18]. Brzeziński et al. [19] studied the effect of cyclic loads on the static strength of the hydraulically bound mixture for use in the pavement structural layers. Results showed the improvement in the strength of the material. It follows from the above that the fatigue life assessment allows the detailed evaluation of the quality of materials to be incorporated in the structural layers. Ensuring the proper values of standard parameters is insufficient to guarantee reliable service of the pavement structure.

The article highlights the importance of assessing the fatigue life of a recycled base with foamed bitumen in the aspect of the stress levels that will probably occur in the rehabilitated pavement structure. The materials used in the structural layers were described by complex modulus master curves. The analysis was performed for the unfavourable temperature distribution at the wearing layer surface temperature of 40°C. This approach made it possible to accurately estimate the complex modulus in the aspect of temperature distribution and depth of the layers. The information obtained was used to build a computational model for the analysis of the tensile stress distribution in the structures. Due to the brittle behaviour of the recycled base layer, it was necessary to determine its durability for the true/modelled stress values. This approach to fatigue life assessment of rehabilitated pavements will secure the recycled base layer with foamed bitumen against cracking due to the cyclic load induced overload.

2. Object of study
The fatigue life analysis of the pavement structure was performed by checking the fatigue life of the recycled mineral-cement mixture with foamed bitumen in the laboratory-based indirect tensile test (ITT). Typical pavement structures (table 1) [20] were selected for the analysis in terms of the 100 kN standard axle load for ranges $5 \times 10^5 < \text{ESAL}_{100\text{kN}} < 2.5 \times 10^6$ (in Poland assigned to the KR3 traffic category) and $2.5 \times 10^6 < \text{ESAL}_{100\text{kN}} < 7.3 \times 10^6$ (in Poland assigned to the KR4 traffic category).

| Layer - material          | Layer thickness in [cm] for $5 \times 10^5 < \text{ESAL}_{100\text{kN}} < 2.5 \times 10^6$ | Layer thickness in [cm] for $2.5 \times 10^6 < \text{ESAL}_{100\text{kN}} < 7.3 \times 10^6$ |
|---------------------------|-------------------------------------------------|-------------------------------------------------|
| Wearing course - SMA11 PMB 45/80-55 | 4.0                                               | 4.0                                               |
| Binder course - AC16W 35/50       | 8.0                                               | 5.0                                               |
| Base course - AC22P 35/50        | -                                                 | 7.0                                               |
| Base course - MCAS 50/70         | 20.0                                              | 20.0                                              |
| Subgrade $E_0 \geq 100$ MPa      | -                                                 | -                                                 |
3. Methods
The procedure applied involved constructing a computational model for which the stiffness modulus E* (MPa) was determined in terms of temperature distribution; the value of stiffness modulus was determined using master curves models for the temperature calculated in the mid-thickness of the layer; the horizontal stress (σₓₓ) distribution at the underside of the structural layers was calculated for the adopted models; and finally, the stress values were used in the recycled base fatigue testing in stress-controlled mode ITT.

3.1. Temperature distribution in the pavement layer system
To analyse the temperature distribution across the thickness of the asphalt layers, typical pavement structures were considered [20]. The history of temperature changes in the layers was determined for the road surface temperature of 40°C (at about 10:30). The temperature distribution was determined using the relationship shown in formula (1) and described in detail in [21, 22, 23]:

\[ T(t, z) = T_M + T_A \cdot \exp(-\lambda z) \cdot \sin \left( 2\pi \cdot \frac{10.4}{24} - \lambda z + \tau \right) \]

where:
- \( T_M \) - average road surface temperature equal to \( T_A = 33.9^\circ C \);
- \( T_A \) - daily road surface temperature change amplitude equal to \( T_A = 16.7^\circ C \);
- \( \lambda \) - a factor dependent on thermal properties of the material;
- \( z \) - the depth of the layer;
- \( \tau \) - correction resulting from the shift of the first measurement time relative to the sine function describing daily temperature changes, equal to \( \tau = 1.25\pi \).

3.2. Master curves of complex modulus E*
The master curve models were developed using the Richards model [24] which is a modification of the model presented in the NCHRP 9-29 report: PP 02 [25]. This model can be classified as a non-symmetrical sigmoid mathematical model owing to the addition of lambda parameter (λ) as an asymmetry coefficient. The form of the sigmoid non-symmetrical function is described by equation (2). Master curves are constructed using the principle of time-temperature superposition. For this purpose, it is necessary to introduce a temperature shift coefficient (α\( T \)) implemented in formula (2) [26]:

\[ \log|E^*| = \delta + \frac{\alpha}{1 + \lambda \omega \gamma \log(a + b T + c T^2)} \]

where:
- \(|E^*|\) – complex modulus,
- \( \omega \) – angular frequency,
- \( \delta \) – the lower asymptote, (master curve fitting parameter),
- \( \alpha \) – the difference between the upper and lower asymptotes, (master curve fitting parameter),
- \( \lambda, \beta, \gamma \) – master curve fitting parameters,
- \( T \) – test temperature,
- \( T_{ref} \) – reference temperature,
- \( a, b, c \) – model parameters.

The complex modulus was determined in the direct compression and tension test (DTC-CY) where the sample is subjected to a cyclic sinusoidal load with a low strain value in the range from 25 to 50 με [27-29]. Testing carried out beyond this strain range may cause irreversible deformations in the sample, leading to errors in the complex modulus. The tests were carried out at four temperatures (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).

3.3. Distribution of the horizontal strains (σₓₓ) in the pavement layer system
To calculate the cooperation between the asphalt layers, the base layer and the underlying native subgrade, a model of statically loaded elastic layers with the assumed full interlaying bonding was used [30]. The load transmitted to the surface was adopted according to [20, 31] in the form of a vertical, uniformly distributed contact pressure of 850 kPa induced by a wheel load of 50 kN (100 kN/axle). The loading time 10 Hz. The distribution of stresses (ε) and strains (σ) in this system was determined.
3.4. Recycled base fatigue in the indirect tensile test ITT
The fatigue of the recycled base course was investigated in accordance with the requirements set forth in PN-EN 12697-24 Annex E [29]. The test samples were subjected to cyclic, compressive loading with a semi-sinusoidal signal. The length of the pulse was 1.5 s and the loading time was 0.124 s. The load was applied through the diametral vertical plane, with a specimen failing by fracturing along the vertical diameter. The strength assessment was performed under stress-controlled conditions. The value of the normal stress used in the test is the result of the stress distribution in the structure calculated at the underside of the recycled base layer as the tensile stress ($\sigma_{x-x}$; $\sigma_{y-y}$). The test was carried out up to 30 load cycles or to the failure of the specimen. Prior to testing, the specimens were preconditioned for four hours at 25°C.

4. Materials

4.1. Basic parameters of the bituminous mixtures and of the recycled mixture MCAS
Materials used in the structural layers intended for rehabilitation in the roadway designed for traffic category KR3 ($5 \times 10^5 < \text{ESAL}_{100kN} < 2.5 \times 10^6$) and KR4 ($2.5 \times 10^6 < \text{ESAL}_{100kN} < 7.3 \times 10^6$) included the SMA11 bituminous mixtures in the wearing layer and asphalt concrete AC bituminous mixtures in the binder and base layers. In the base layer for the KR3 and KR4 traffic, a cold foamed bitumen mineral-cement mix was also used. The gradation curves of these mixtures are shown in Fig. 1.

![Figure 1. Grading curves of the mineral mixtures.](image)

The bituminous mixtures SMA11, AC16W and AC22P were designed to the requirements set forth in WT-2 2014 [32], and the mineral-cement mix with foamed bitumen (MCAS) was designed to the specifications contained in [33, 34]. The results of the basic properties of the mixtures under analysis are summarized in Table 2.

| Property                              | Symbol | u.m.    | SMA11 | AC16W | AC22P | MCAS       |
|---------------------------------------|--------|---------|-------|-------|-------|------------|
| Bitumen/cement content                | B / C  | [%]     | 6.3   | 4.6   | 3.9   | 2.4        |
| Water sensitivity, PN-EN 12697-12, + [32]| TSR   | [%]     | 95.0  | 89.9  | 84.2  | -          |
| Moisture resistance, Wirtgen 2006 [33]| TSR   | -       | -     | -     | 99.9  | -          |
| Void characteristics, PN-EN 12697-8   | $V_m$  | [%]     | 3.0   | 4.3   | 5.6   | 10.6       |
| Indirect tensile strength, PN-EN 12697-23 (T=25°C) | ITS    | [kPa]   | 822   | 1133  | 994   | 546        |

Table 2. Basic parameters of the mixtures.
Propor

Proportional rut depth (small device, 60°C, 10000 cycles)  \( \text{PRD}_{\text{AIR}} \) [%]  5.4  3.9  4.8  -

Wheel-tracking slope (small device, conditioning in air, 60°C, 10000 cycles),  \( \text{WT}_{\text{SIAIR}} \) [mm/1000cycle]  0.06  0.05  0.08  -

Binder drainage, % m/m, (at production temperature, Schellenberg’s method)  \( D \) [% (m/m)]  0.20  -  -  -

4.2. Complex modulus master curves for the mixtures

The principles of time-temperature superposition [25, 35] were used to build the complex modulus master curves of the bituminous and MCAS mixtures [25, 35]. The sigmoid function was optimized by minimizing the sum of squared deviations for the complex moduli determined. The master curve coefficients \( (\alpha, \beta, \gamma, \delta, \lambda, a, b, c) \) had to be determined from the observed data in the optimization process. The criterion of the normalized root-mean-square error \( \text{RMSE} \), applied by the authors to the evaluation of the SMA behavioral changes [36], was used to assess the goodness-of-fit of the sigmoid function. The parameter assessment results are shown in Table 3.

| Mixture   | Master curve fitting parameters | Goodness-of-fit |
|-----------|-------------------------------|----------------|
|           | \( \alpha \) | \( \beta \) | \( \gamma \) | \( \delta \) | \( \lambda \) | a | b | \( R^2 \) |
| SMA11     | 2.278 | 0.362 | -0.443 | 2.278 | 0.143 | 2.01 | -0.048 | 0.97 |
| AC16W     | 2.177 | 0.299 | -0.492 | 2.177 | 0.21 | 2.24 | -0.047 | 0.95 |
| AC22P     | 2.083 | 0.35 | -0.400 | 2.083 | 0.3 | 2.32 | -0.034 | 0.97 |
| MCAS      | 2.149 | 1.035 | -0.224 | 2.149 | 0.1 | 2.572 | -0.014 | 0.98 |

The very high value of \( R^2 \) for the non-symmetrical sigmoid function model fitting parameters confirms the good fit of the function to the determined values of the complex modulus shifted by a value of \( \alpha_T \). Analysis of the master curve "\( \lambda \)" parameter showed variations in the behaviour of the mixtures. The highest complex modulus variation at low and high temperatures was observed in the SMA11 mix. It should also be noted that SMA11 in the case of a long loading time (at high temperatures) showed the lowest value of the complex modulus in comparison to the other analysed mixtures. This is a disadvantageous phenomenon from the point of view of plastic deformation.

The master curves in the reduced frequency domain at a reference temperature of 25°C are shown in Fig. 2.

![Figure 2. Master curves (T_{ref}=25°C) for the tested mixtures.](image-url)
It is evident (Fig. 2) that at very low frequencies (below 0.1 Hz) the complex modulus correlates with the quantity of bitumen in the bituminous mix. The SMA11 mix, containing the highest bitumen amount, shows the lowest module. This behaviour adversely affects the bituminous mix layer designed for the wearing course, where long loading time will quickly change its properties. A similar relationship in terms of loading time in SMA mixes was reported in [31]. Also, the asphalt concrete mixture for use in the binder layer, AC16W 35/50, containing 4.6% bitumen, behaves in a similar manner at the early stage of loading. However, below 10 Hz, the AC16W mixture has a higher stiffness modulus than the SMA11 mixture. This phenomenon may be related to the higher quantity and softer type of the bitumen in the SMA11 mixture. Mixtures designed for base layers, such as AC22P and MCAS, demonstrate a similar rate of complex modulus variation as a function of loading time. Nevertheless, the recycled base with foamed bitumen MCAS will have better parameters at long and short loading times. Under very slow traffic (vehicle speed of less than 0.5 km/h), the complex modulus of MCAS is higher than the modulus of the AC22P mixture by over 1000 MPa. This behaviour will reduce the vertical strain in the subgrade and thus increase the fatigue life.

5. Results of the calculations and analyses

5.1. Computational model

The computational model for the typical structures being analyzed was constructed using the dependence (1) described in detail in [21, 22, 23]. The temperature in the rehabilitated roadway structures was defined at the mid-thickness of the layer. The value of the complex modulus at a given temperature in the layer was determined using the characteristics obtained from the master curve models. As a result, comprehensive information was collected for the determination of the stress distribution in the pavement structures. The results of the analysis are presented in Table 4.

Table 4. Computational model for the structures being analysed.

| Layer - material | Layer thickness for 5x10^5<ESAL_100kn<2.5x10^6 | Layer thickness for 2.5x10^6<ESAL_100kn<7.3x10^6 |
|------------------|---------------------------------------------|-----------------------------------------------|
|                  | h [m] t [°C] ν [-] E * (10Hz) [MPa]          | h [m] t [°C] ν [-] E * (10Hz) [MPa]           |
| Wearing - SMA11 PMB 45/80-55 | 0.04 37.0 0.40 4453 | 0.04 37 0.40 4453 |
| Binder - AC16W 35/50      | 0.08 32.0 0.40 6483 | 0.05 32 0.40 6483 |
| Base - AC22P 35/50        | - - - - | 0.07 30 0.40 5855 |
| Subbase - MCAS 50/70      | 0.20 31.0 0.40 4925 | 0.20 31.0 0.40 4925 |
| Subgrade E≥100 MPa        | - - 0.35 100 | - - 0.35 100 |

The values of complex modulus obtained from the master curves are lower than those recommended for the calculation of fatigue life in Poland [20]. The differences between measurement temperatures affect those values.

5.2. Determination of the stress and strain states using the FEM

The layer system was modeled in ABAQUS. The mesh of elements was constructed with the assumption that the minimum dimension of the element is 4 cm and there is a minimum of four elements in one layer of the pavement structure. A basic eight-node finite element with quadratic shape functions (CAX8) [37] was used for analysis. The computational region in the analysis was 5 m (height) and 3.5 radius (rotationally symmetric model). The side edges and the base had pinned joint (connection). The distribution of stresses for the analyzed typical structures was determined. The
results of the analysis in the form of stress distribution maps for the structure are shown in Fig. 3. The values of horizontal stresses ($\sigma_{x-x}$; $\sigma_{y-y}$) for individual points in the structure are provided in Table 5.

![Figure 3. Distribution of stresses in the KR3 (5x10^5<ESAL100kN<2.5x10^6) pavement structure.](image)

![Figure 4. Distribution of stresses in the KR4 (2.5x10^6<ESAL100kN<7.3x10^6) pavement structure.](image)

### Table 5. Computational model of the structures being analysed.

| Layer - material | KR3 5x10^5<ESAL100kN<2.5x10^6 | KR4 2.5x10^6<ESAL100kN<7.3x10^6 |
|------------------|-------------------------------|---------------------------------|
|                  | Depth pkt. [m] | [kPa] | Depth pkt. [m] | [kPa] |
| Wearing - SMA11 PMB 45/80-55 | 0.0000 | -1214.3 | 0.0000 | -1112.3 |
| Binder - AC16W 35/50 | 0.0399 | -924.9 | 0.0399 | -860.7 |
| Base - AC22P 35/50 | 0.0401 | -919.3 | 0.0401 | -873.1 |
| Subbase - MCAS 50/70 | 0.1199 | -218.9 | 0.0899 | -472.7 |
| Subgrade $E_r\geq100$ MPa | 0.1599 | -103.7 | 0.1601 | -384.9 |

The tensile stress values ($\sigma_{x-x}$; $\sigma_{y-y}$) at the underside of the recycled base layer for the KR3 structure (5x10^5<ESAL100kN<2.5x10^6) is 669.3 kPa and 555.1 kPa for the KR4 structure (2.5x10^6<ESAL100kN<7.3x10^6). Increased thickness of the package of bituminous mix-based layers decreases tensile stresses in the base layer produced with the mineral-cement mixture with foamed bitumen, MCAS, thus contributing to reduced vertical strain in the subgrade and improved fatigue life of the system as a whole. The values of the tensile stress are similar to the values of indirect tensile strength (ITS$_{DRY}=546$ kPa) characteristic of the recycled base with foamed bitumen. As this may confirm a probability of overloading/cracking of the base layer due to unfavourable weather conditions, which indicates the need for monitoring the structures' performance and implementing preventive measures to ensure longevity and safety.
conditions (high temperature), it seems necessary to evaluate the fatigue life of the mineral-cement mixture with foamed bitumen for use in the base layer. Determining the fatigue life under dynamic loading in the indirect tensile test will contribute to a more accurate quality evaluation of the mineral-cement mix with foamed bitumen designed for use in the base layer during road rehabilitation works.

The fatigue test was performed on cylindrical samples in an indirect tensile test in accordance with the requirements of PN-EN 12697-24, Annex E [29], for two stress levels, 375 kPa and 500 kPa. These values are close to the values of stresses occurring in the structures under analysis. The fatigue characteristics of the recycled base with foamed bitumen are shown in Figure 5.

![Fatigue curves of the MCAS recycled base.](image)

Figure 5. Fatigue curves of the MCAS recycled base.

Note that the increase in the stress level in the tested recycled base samples increased the initial strain value. At a stress of 375 kPa, the strain after the 100th load cycle was 58 μm, while at 500 kPa the initial strain was 185 μm. Furthermore, throughout the testing period, i.e., 30,000 load cycles at a stress of 375 kPa, only a 29% increase in strain relative to the initial value was found. Different fatigue characteristics were obtained in the study of the recycled base with foamed bitumen at a stress of 500 kPa, where after 800 load cycles the sample failed.

The results above support the observation that the increase in the stress level has a destructive effect on the quality of the recycled base layer and that attaining the required basic quality parameters does not guarantee road rehabilitation reliability. The indirect tensile strength values (ITSTDRY) exceeding the value of the stress level used in this study does not ensure the required life. Dynamic testing is a better tool for discriminating the quality of the recycled base.

6. Conclusions

Based on the results of this study, the following conclusions are offered:

- As for the asphalt mixes evaluated, at very low frequencies below 0.1 Hz, the complex modulus correlates with the bitumen content. The lowest value of the complex modulus E* was obtained for the SMA11 mixture (with B = 6.4%) and the highest value E* for the asphalt concrete AC22P (B = 3.9%) and MCAS (B = 2.0%). This is due to the sensitivity of the bitumen to the deformation in a long loading time,
- An increase in the thickness of asphalt layer package contributes to the reduction of tensile stress (\(\sigma_{xx}, \sigma_{yy}\)) in the recycled base layer made with mineral-cement mixture and foamed bitumen, MCAS,
- Increased stress level in the fatigue life test of the recycled base with foamed bitumen affected the initial strain value and showed a deleterious effect on the durability/strength of the mineral-cement mixture with foamed bitumen,
• application of the mineral-cement mixture with foamed bitumen to the KR3 traffic category (5x10^3<ESAL_{100kN}<2.5x10^6) roads, where the horizontal stress derived from the computational model is 669.1 kPa, does not guarantee the reliability of the road rehabilitation works. The stress level of 500 kPa led to the premature failure of the MCAS sample after 800 cycles of dynamic loading,

• quality assessment through dynamic testing should be employed when the value of indirect tensile strength (ITSD_{DAR}) is close to the value of horizontal stress in the structure in which the recycled base layer is planned to be used.

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