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# Reusability of reclaimed asphalt from SMA layers: extended evaluation of recovered polymer-modified bitumen properties

**Abstract:** The article presents the results of research aimed at evaluating the properties of asphalt binders recovered from material obtained during milling of polymer-modified SMA layers. Laboratory tests were carried out on asphalts recovered from RAP, on blends in defined proportions with fresh polymer-modified binders, as well as on binders recovered from SMA mixtures containing reclaimed asphalt. The study's scope included standard classification tests of polymer-modified binders and an assessment of rheological properties using the MSCR method. An analysis of the results was performed to evaluate the condition of the recovered binders and to select binders for blending with fresh PMB and reclaimed aggregates for the design of SMA mixtures with RAP. The analysis of blends and recovered binders enabled a relative evaluation of binder properties, indicating variants that may potentially require the application of rejuvenators. The presented research constitutes one of the stages of the rSMA2 project focused on the recycling of SMA layers.

**Keywords:** polymer-modified bitumen, reology, reclaimed asphalt pavement, recycling, SMA.

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# 1. INTRODUCTION

Recycling of asphalt pavements represents one of the key activities in the pursuit of sustainable road infrastructure development. Its significance arises from both environmental and economic aspects. Asphalt binder, as a thermoplastic material, is characterized by the possibility of repeated processing – when heated, it becomes plastic, and upon cooling, it returns to a solid state. This property enables the recovery and reuse of asphalt mixtures, including reclaimed asphalt pavement (RAP), which contains valuable resources: asphalt binder and mineral aggregates.

Of particular importance in this context are surface layers, especially those produced from stone mastic asphalt (SMA) mixtures, which contain high-quality aggregates and asphalts, in particular polymer-modified binders. This translates into the high technical value of SMA-derived RAP. One of the decisive factors determining the quality of reclaimed asphalt is the condition of the binder, which undergoes aging processes both during technological operations and during service life. These changes make the binder stiffer, reduce its viscoelastic properties, increase its susceptibility to cracking, and lower its resistance to deformation. In the case of polymer-modified binders, aging also affects the polymer phase itself, which undergoes oxidation and loses part of its elastic properties [1, 2]. FTIR spectroscopy studies have demonstrated that ageing processes occur both in the bituminous binder itself and in the polymer. The ageing of the asphalt phase associated with oxidation is the dominant process, while polymer degradation becomes more significant at lower temperatures and shorter ageing durations [3]. Highly modified binders, i.e., those with an increased polymer content, may exhibit greater resistance to ageing than conventional polymer-modified bitumens, provided that the recommended technological temperatures are maintained during the production of the asphalt mixture [4]. The properties of aged binder in RAP are of critical importance for the asphalt mixture produced with the addition of reclaimed asphalt. The higher the RAP content, the more significant this influence becomes [5].

In principle, it can be expected that the addition of RAP will improve rutting resistance [6], but there are also situations where it may have adverse effects [7] (such as reduced low-temperature cracking resistance [8-11] and fatigue resistance [12-14]). Another issue that must be considered simultaneously is the compatibility of the "aged" and "fresh" binders, which significantly affects the properties of the asphalt mixture. The degree of blending depends on many factors, including mixing time and temperature [15, 16], the type of fresh asphalt used [17], and the degree of binder aging [18]. Research studies have addressed the questions of whether the binders blend only partially, fully, or whether the situation corresponds merely to fresh asphalt coating the "black rock" particles [19, 20]. Assessing binder compatibility is also a complex task, requiring the use of advanced spectrographic methods [21]. To enhance binder compatibility and improve the properties of aged asphalt, special additives known as rejuvenators are employed [22, 23].

In Poland, the recycling of SMA wearing courses is of particular importance due to the upcoming need for modernization and rehabilitation of roads constructed 15-20 years ago, including a large portion of roads managed by GDDKiA (General Directorate for National Roads and Motorways), where SMA has been the dominant mixture in the wearing course. The use of RAP in surface layers involves a higher risk compared to lower layers and therefore has not been widely applied; previous technical guidelines in Poland introduced certain restrictions in this regard. Consequently, in 2023, a research program titled rSMA2, "Development of guidelines for the reuse of reclaimed asphalt from SMA layers for new SMA wearing courses" was launched. The project, carried out by three research institutions, featured an extensive research program, with one of the first stages focused on identifying the properties of asphalts in selected RAP sources in the context of using reclaimed material in new SMA mixtures.

This article aims to evaluate the properties of asphalt binders recovered from materials obtained during the milling of polymer-modified SMA layers, as part of the rSMA2 project. Laboratory tests were carried out on asphalts recovered from RAP, on blends in defined proportions with fresh polymer-modified binders, as well as on binders recovered from SMA mixtures containing reclaimed asphalt. The study's scope included standard classification tests of polymer-modified binders and an assessment of rheological properties using the MSCR method. An analysis of the results was performed to evaluate the condition of the recovered binders and to select binders for blending with fresh PMB and reclaimed aggregates for the design of SMA mixtures with RAP. The analysis of blends and recovered binders enabled a relative evaluation of binder properties, indicating variants that may potentially require the application of rejuvenators.

## 2. MATERIALS AND TEST METHODS

The materials used for the study included two polymer-modified binders commonly applied in SMA mixtures, namely PMB 45/80-55 (designated further as PMB55) and PMB 45/80-65 (PMB65), as well as three reclaimed asphalt pavements (RAP) obtained through selective milling of SMA wearing courses:

- A1 – RAP obtained from milling of the A1 motorway pavement top layer, SMA11 mixture with DE 80B polymer-modified binder (equivalent to PMB 45/80-55), service life: 14 years,
- S7 – RAP obtained from milling of the S7 expressway pavement top layer, SMA11 mixture with PMB 45/80-55, estimated service life: 8-12 years,
- CH – RAP obtained from milling of a top layer of the street in Warsaw, SMA8 mixture with PMB 45/80-65 polymer-modified binder, service life: 13 years.

The selection of reclaimed asphalt was determined by several factors, including their age, representativeness in terms of mixture type and gradation, the materials used, and in particular, the types of polymer-modified binders. The RAP materials were subjected to testing according to the requirements of PN-EN 13108-8 [24], which also requires the determination of asphalt binder properties. For this purpose, binder recovery was carried out in accordance with PN-EN 12697-3 [25]. The binder testing program included penetration at 25°C according to PN-EN 1426 [26] and softening point temperature according to PN-EN 1427 [27]. These two tests are the basic requirements of PN-EN 13108-8; however, since the binders under study were polymer-modified, the scope was extended to include elastic recovery according to PN-EN 13398 [28], Fraass breaking point according to PN-EN 12593 [29], and rheological properties using the MSCR method according to PN-EN 16659 [30]. The elastic recovery test provides an excellent illustration of the characteristic properties of PMB binders [31, 32] and is also required by the standard for polymer-modified binders, PN-EN 14023 [33]. The Fraass breaking point test determines the susceptibility of asphalt to cracking at sub-zero temperatures, which, given the climatic conditions in Poland [34, 35] is a mandatory test for all asphalts. The final method applied was the evaluation of rheological properties using the MSCR (Multiple Stress Creep Recovery) test, carried out with a Dynamic Shear Rheometer (DSR) [36]. This test consists of repeatedly loading and unloading the sheared specimen with a stress impulse at maximum shear stress values of 0.1 kPa and subsequently 3.2 kPa. The test is conducted at a temperature of 60°C. Based on the test results, the parameters $R$_0.1kPa and $R$_3.2kPa are determined, which are interpreted as the elastic recovery under shear, expressed in %. In addition, the so-called non-recoverable creep compliance values $J_{nr}$_0.1kPa and $J_{nr}$_3.2kPa are determined (the higher the compliance, the greater the susceptibility to permanent deformation, which in turn translates into rutting of the asphalt mixture containing the tested binder).

The MSCR test is intended to provide a rational assessment of polymer-modified binders. The most common way of presenting the test results is to plot them on a diagram with $J_{nr}$_3.2kPa on the $x$-axis and $R$_3.2kPa on the $y$-axis (the higher stress level is used for PMBs, while the lower level is typically used for conventional paving asphalts) and then determine whether the results are located above or below the curve defined by eq. (1), cf. [37, 38]:

$$y\,(x) = 29.317 \cdot x^{-0.2633}, \tag{1}$$

where:

$x = J_{nr}$_3.2kPa – non-recoverable creep compliance at the stress level of 3.2 kPa [1/kPa],

$y = R$_3.2kPa – elastic recovery in shearing mode at the stress level of 3.2 kPa [%].

The MSCR test is useful both for characterizing the properties of polymer-modified binders [39, 40], but also for assessing the degree of their aging [41].

The binder tests were carried out in three stages. In the first stage, tests were performed on polymer-modified binders PMB55 and PMB65 as well as on binders recovered from RAP, followed by an analysis of the results, on the basis of which two binders were selected for further testing. In the second stage, blends of recovered asphalts and polymer-modified binders were prepared in proportions corresponding to the binder replacement ratio (BR), defined by the following eq. (2):

$$BR = \frac{a \cdot b}{c}, \tag{2}$$

where:

*a* – content of binder soluble in RAP [% (m/m)],

*b* – RAP content in the asphalt mixture [% (m/m)],

*c* – total binder content soluble in the asphalt mixture [% (m/m)].

Two levels of the *BR* index were adopted, equal to 30% and 50%, respectively. The lower BR level corresponds to the maximum value permitted for use in Poland, whereas the higher value was adopted to assess the potential for increasing the RAP content in asphalt mixtures, in accordance with the research plan established for this rSMA2 project. In the third stage, tests were carried out on binders recovered from the designed SMA mixtures at *BR* = 0%, 30%, and 50%.

## 3. PRESENTATION OF THE EXPERIMENTAL RESULTS

### 3.1. TESTS OF POLYMER-MODIFIED BINDERS AND BINDERS RECOVERED FROM RAP

Figs 1-3 present the results of binder tests concerning penetration, softening point, Fraass breaking point, elastic recovery, and rheological properties determined by the MSCR test. The tests were carried out on binders recovered from RAP as well as on polymer-modified binders supplied from the refinery in three aging states: unaged, short-term aged (S) after RTFOT, and long-term aged (L) after RTFOT + PAV. Each of the presented charts shows two investigated properties, with shaded areas representing the 95% confidence interval ranges. Mean values are indicated as the geometric centre of each rectangle. The results of polymer-modified binders at different aging levels are included to enable comparison with the results obtained for binders recovered from RAP. Table 1 provides a summary of the mean values of the parameters obtained.

Fig. 1 presents the penetration and softening point results, which are the fundamental parameters defining the consistency of asphalts. Analysing the results of polymer-modified binders PMB 45/80-55 and PMB 45/80-65, it can be observed that they confirm the well-known relationship that aging processes lead to binder hardening, i.e., penetration values decrease while softening point temperatures increase. It can also be stated that the properties of the recovered binders are shifted into the range located between the results of polymer-modified binders after short-term and long-term aging.

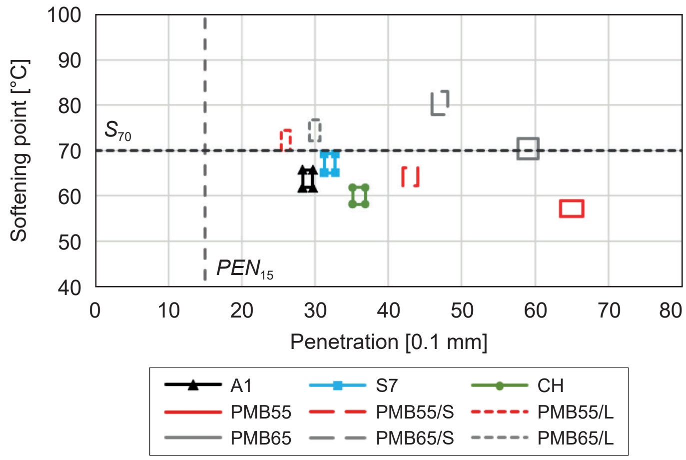


Fig. 1. Penetration and softening point results of polymer-modified binders in three aging states and binders recovered from RAP (95% confidence interval)

The penetration and softening point results confirm that the binders have undergone aging processes as a consequence of technological procedures and pavement service life. Binders A1 and S7 exhibit properties more similar to polymer-modified binders after RTFOT + PAV aging, i.e., lower penetration and higher softening point temperatures than binder CH. It should be noted, however, that these values generally do not exceed the limit values for binders

Table 1. Test results of recovered binders and polymer-modified binders in three aging states

| Material labelling | A1 | S7 | CH | PMB55 | PMB55/S | PMB55/L | PMB65 | PMB65/S | PMB65/L |
|---|---|---|---|---|---|---|---|---|---|
| Penetration [0.1 mm] | 29.0 | 32.0 | 36.0 | 65.0 | 43.0 | 26.0 | 59.0 | 47.0 | 30 |
| Softening point [°C] | 63.8 | 67.2 | 60.0 | 57.2 | 64.2 | 72.2 | 70.4 | 80.5 | 74.4 |
| Fraass braking point [°C] | −8.0 | −15.0 | −12.0 | −21.0 | −20.0 | −14.0 | −21.0 | −23.0 | −18 |
| Elastic recovery [%] | 69.0 | 71.0 | 80.0 | 85.0 | 85.0 | 77.0 | 89.0 | 88.0 | 75 |
| *R*_3.2kPa [%] | 32.5 | 62.5 | 30.8 | 40.1 | 53.2 | 65.8 | 74.5 | 81.2 | 79.39 |
| $J_{nr}$_3.2kPa [1/kPa] | 0.2 | 0.2 | 0.5 | 0.7 | 0.3 | 0.1 | 0.2 | 0.1 | 0.05 |

recovered from RAP as specified in PN-EN 13108-8. According to this standard, the mean penetration at 25°C should not be lower than 15 units (0.1 mm), and the mean softening point should not be higher than 70°C (the limits are marked in the Fig. 1 as $PEN_{15}$ and $S_{70}$, respectively). Naturally, it must be emphasized that these requirements are primarily defined for paving-grade asphalts, and in the case of polymer-modified binders, they are insufficient to fully determine their properties and degree of aging.

Further information on the properties of PMB binders recovered from RAP is provided by the results presented in the subsequent figures. In terms of low-temperature cracking resistance according to the Fraass method, the properties of the recovered binders differ significantly, with the best result (i.e., the lowest breaking point temperature) obtained for binder S7 and the highest for binder A1 (Fig. 2). The range of mean values for the recovered binders is between −8°C and −15°C. It should be noted that the best result (binder S7) meets the requirement of PN-EN 14023 (breaking point temperature ≤ −15°C, marked in the figure as $T_{Fr-15}$). The obtained results are relatively less favourable when compared to PMB55 and PMB65 binders. Polymer-modified binders aged under laboratory conditions yielded mean values of −20°C and −23°C after technological aging and −14°C and −18°C after long-term aging, respectively.

For elastic recovery, the results of binders A1, S7, and CH are less differentiated, with mean values of 69%, 71%, and 80%, respectively (Fig. 2). These results can be positively evaluated with regard to the requirements of PN-EN 14023, which for unaged binders are specified at not less than 70% ($ER_{70}$) in the case of PMB 45/80-55 and not less than 80% ($ER_{80}$) in the case of PMB 45/80-65. However, in comparison with the results of PMB55 and PMB65, it can be stated that the obtained values are close to the mean results of binders after long-term aging, which amounted to 77% and 75%, respectively. Results after short-term aging were at the level of 85-88%.

In summary, the results shown in Fig. 2 indicate that, with respect to low-temperature cracking resistance and elastic recovery, the properties of the recovered binders clearly reflect the influence of aging processes.

Analysing the MSCR test results (Fig. 3), it can be concluded that among the group of recovered binders, only binder S7 falls within the range expected for polymer-modified binders. The results of binders A1 and CH are shifted toward lower values of elastic recovery under shear $R$_3.2kPa and higher non-recoverable compliance $J_{nr}$_3.2kPa. In contrast, binder S7 is characterized by a high recovery value of approximately 65% and a compliance level of 0.17 1/kPa. In this respect, its properties are comparable to those of PMB65 in the unaged state and PMB55 after aging.

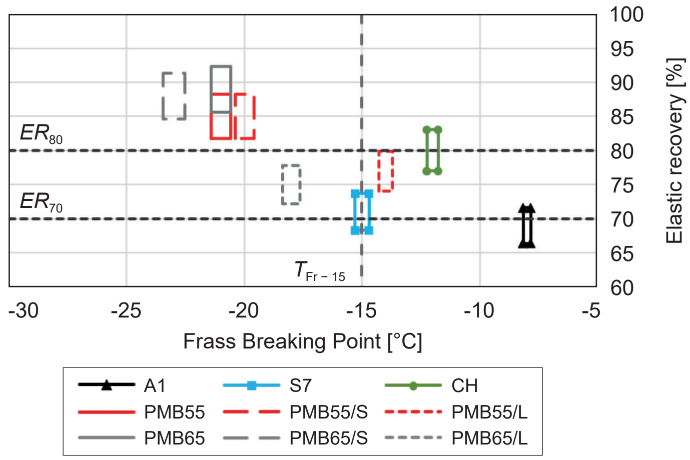


Fig. 2. Fraass breaking point and elastic recovery results of polymer-modified binders in three aging states and binders recovered from RAP (95% confidence interval)

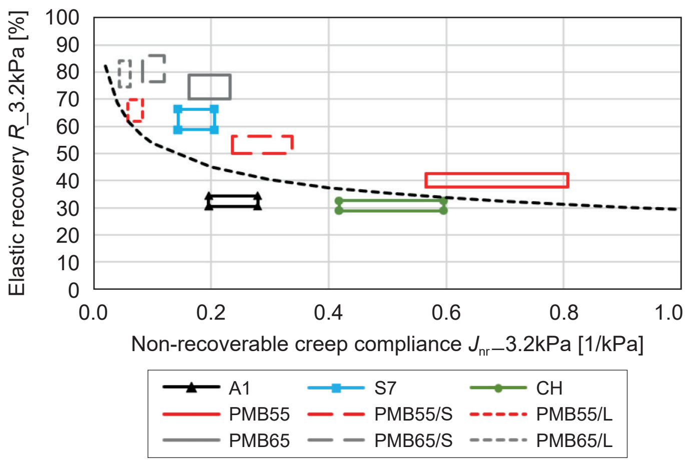


Fig. 3. MSCR test results of polymer-modified binders in three aging states and binders recovered from RAP (95% confidence interval)

Summarizing the results of the tests and the evaluation of binders recovered from RAP, it can be stated that, with respect to the properties characteristic and expected for polymer-modified binders, they show considerable variation. The best performance was observed for binder S7, which was particularly distinguished by its rheological properties according to the MSCR test and by its favourable

Fraass breaking point temperature. Considering the objectives of the project, binders CH and A1 were selected for further research, as these will require additional measures in order to meet the relevant normative requirements in new SMA mixtures.

## 3.2. TESTS OF BLENDS OF RECOVERED BINDERS AND POLYMER-MODIFIED BINDERS

According to the project assumptions, SMA RAP will be reused as a component of a new SMA mixture. Consequently, the binder contained in the RAP will, during the production of the new mixture, be blended with fresh polymer-modified binder. Therefore, in the next stage of the study, the properties of blends of recovered binders A1 and CH with fresh binders PMB55 and PMB65 were analysed at two proportions corresponding to binder replacement ratios $BR$ = 30% and 50% (i.e., 70/30 and 50/50 fresh/recovered). The blends were prepared in two ways. In the first method, recovered binders were mixed with polymer-modified binders in defined proportions and designated as CH/30/PMB65, CH/50/PMB65, A1/30/PMB55, and A1/50/PMB55. In the second method, SMA8 PMB 45/80-65 and SMA11 PMB 45/80-55 mixtures were prepared with $BR$ = 0%, 30%, and 50%, designated respectively as CH/0/M65, CH/30/M65, CH/50/M65, A1/0/M55, A1/30/M55, and A1/50/M55.

This approach is approximate, since it is difficult to determine the extent to which the production process allows blending between the fresh binder and the binder from RAP. It is also known that the binder recovery process itself may influence the results. Nevertheless, the conducted tests are intended to provide a preliminary assessment of the properties of the resulting binder. They may also be potentially useful in evaluating the need for the use of recycling additives, i.e., so-called rejuvenators. The results in the form of mean values are presented in Table 2, while the values with 95% confidence intervals are shown in Figs. 4-9.

Fig. 4 presents the penetration and softening point results of the blend of CH binder and PMB65, as well as of the binder recovered from the SMA8 PMB65 mixture with CH RAP at $BR$ = 0%, 30%, and 50%. The results of the blended binders and the binders recovered from the SMA mixtures show lower softening point values compared to the PMB65 binder results, regardless of their aging state, while penetration values fall within the range of short-term and long-term aged PMB65. It should be noted that the results of the blends and recovered binders are only slightly differentiated in terms of softening point $T_{R\&B}$, but more noticeably differentiated in terms of penetration. Increasing the proportion of RAP binder in the blend and the RAP content in the mixture leads to a reduction in both penetration and softening point. The consistency of the binder in the blend or mixture with $BR$ = 50% is similar to that of the binder recovered from CH RAP.

Table 2. Test Results of PMB65 binder blends with CH recovered binder

| Material labelling | CH/30/PMB65 | CH/50/PMB65 | CH/0/M65 | CH/30/M65 | CH/50/M65 |
|---|---|---|---|---|---|
| Penetration [0.1 mm] | 45 | 40 | 49 | 40 | 35 |
| Softening point [°C] | 63.0 | 61.6 | 65.2 | 64.0 | 64.2 |
| Fraass braking point [°C] | −15 | −13 | −20 | −16 | −15 |
| Elastic recovery [%] | 80 | 79 | 84 | 79 | 74 |
| $R$_3.2kPa [%] | 39 | 37 | 65 | 55 | 49 |
| $J_{nr}$_3.2kPa [1/kPa] | 0.42 | 0.44 | 0.24 | 0.26 | 0.25 |

Table 3. Test results of PMB55 binder blends with A1 recovered binder

| Material labelling | A1/30/PMB55 | A1/50/PMB55 | A1/0/M55 | A1/30/M55 | A1/50/M55 |
|---|---|---|---|---|---|
| Penetration [0.1 mm] | 45 | 39 | 39 | 31 | 30 |
| Softening point [°C] | 59.4 | 60.0 | 60.0 | 62.7 | 63.6 |
| Fraass braking point [°C] | −16 | −14 | −20 | −18 | −15 |
| Elastic recovery [%] | 80 | 76 | 79 | 76 | 73 |
| $R$_3.2kPa [%] | 28 | 32 | 37 | 42 | 41 |
| $J_{nr}$_3.2kPa [1/kPa] | 0.50 | 0.58 | 0.44 | 0.27 | 0.24 |

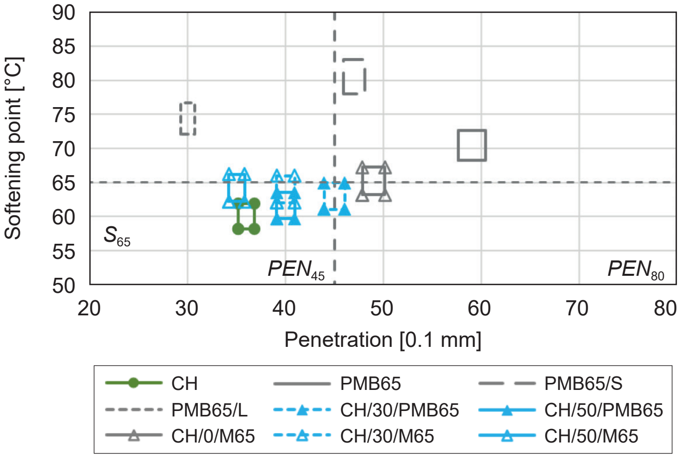


Fig. 4. Penetration and softening point results of PMB65 and blends with binder recovered from CH RAP (95% confidence interval)

An analogous analysis can be carried out for the binder and RAP A1, as well as for the binder recovered from the SMA11 PMB55 mixture with A1 RAP at *BR* = 0%, 30%, and 50% (Fig. 5). In this case, it can also be observed that the softening point results of binders recovered from SMA11 mixtures and of binder blends show little differentiation and are lower than those of PMB55 at various aging states. The penetration of these binders is more differentiated and falls within the range of PMB55 after short- and long-term aging. Consistency changes with increasing RAP content and the proportion of "aged" binder. Increasing the BR index shifts the properties toward those of the recovered A1 binder and those of PMB55 after long-term aging.

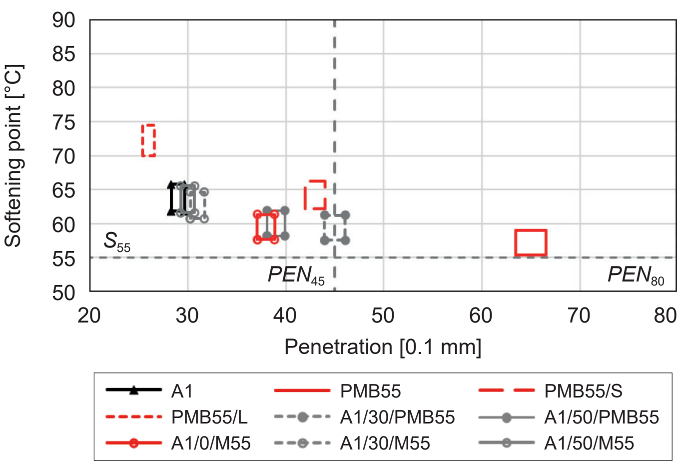


Fig. 5. Penetration and softening point results of PMB55 and blends with binder recovered from A1 RAP (95% confidence interval)

Figs. 6 and 7 present the results of the Fraass breaking point and elastic recovery tests. For both CH and A1 binders and their blends, it can be clearly stated that mixing with fresh binder has a beneficial effect on low-temperature properties. For the first material, the breaking point temperature of the recovered CH binder was −12°C, while in the blend with PMB65 it ranged from −13°C to −16°C. In the case of binder A1, the effect of blending with fresh PMB55 on low-temperature properties is even more evident: the breaking point temperature of the recovered binder alone was −8°C, while after blending with PMB55 it ranged from −14°C to −18°C.

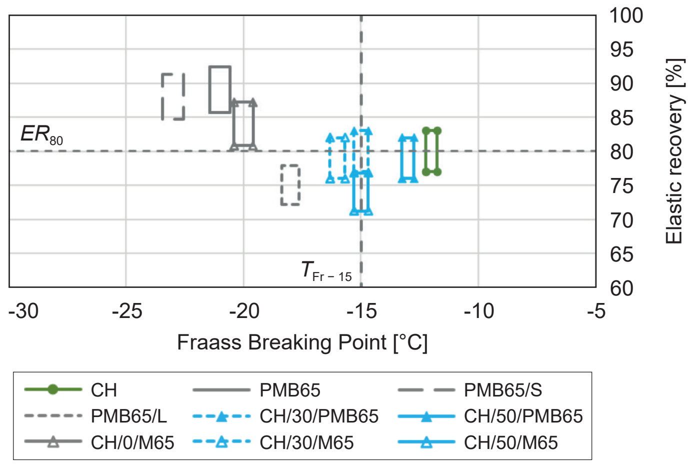


Fig. 6. Fraass breaking point and elastic recovery results of PMB65 and blends with binder recovered from CH RAP (95% confidence interval)

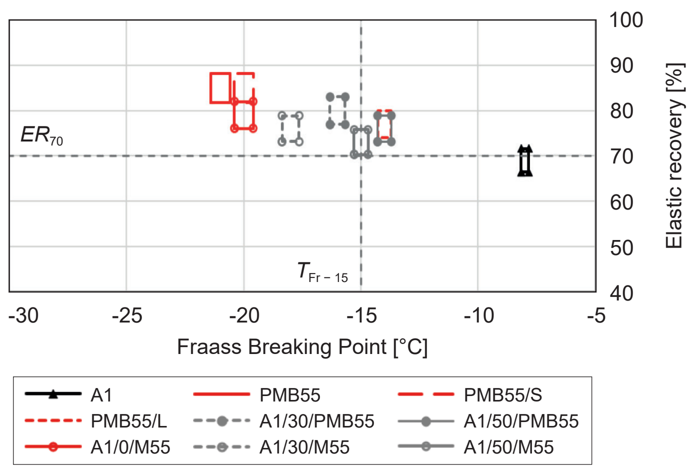


Fig. 7. Fraass breaking point and elastic recovery results of PMB55 and blends with binder recovered from A1 RAP (95% confidence interval)

For both materials, the breaking point temperatures of binders recovered from RAP were slightly more favourable than those of laboratory-prepared blends. The blends in the form of binders recovered from SMA8 and SMA11 mixtures with CH and A1 RAP, respectively, met the requirements for fresh binders according to PN-EN 14023. Nevertheless, these results are weaker than the breaking point temperature of the binder recovered from the SMA mixtures with PMB65 and PMB55, which in both cases reached −20°C.

The conclusions from the elastic recovery test results are less clear. For binder A1, in every case, the RAP binder blended with fresh binder showed a favourably higher elastic recovery than the recovered A1 binder itself (results from 73% to 80% compared to 69%). For the second material (CH), blending with fresh binder did not increase elastic recovery. The results ranged from 74% to 80%, with the highest value corresponding to the recovered CH binder. The elastic recovery of PMB65 binder recovered from the SMA8 mixture without RAP was the highest among all results, at 84%.

Considering both the breaking point temperature and elastic recovery results, it can be concluded that increasing the RAP content from 30% to 50% led to their deterioration. However, when comparing the obtained results to the requirements of PN-EN 14023 for PMB 45/80-55 and PMB 45/80-65, they can be evaluated positively, since in every case the requirement for unaged binders was met (70% and 80%, respectively).

The final stage of the analysis comprises the MSCR test results. For the CH and PMB65 binder blend, a clear improvement in properties is observed, shifting toward the range of values favourable for polymer-modified binders. This is particularly evident in the results of binders recovered from the SMA8 mixture with CH RAP (Fig. 8). The PMB65 binder recovered from the mixture without RAP shows better elastic recovery under shear, with a similar level of non-recoverable creep compliance. Blends with a lower RAP binder content are characterized by higher elastic recovery. The mean results of CH-PMB65 blends prepared in the laboratory are located slightly above the boundary curve in the analysed diagram.

The results obtained with A1 material (Fig. 9) are more complex to interpret. The properties of the blends of A1 recovered binder and PMB55 do not meet the criteria for polymer-modified binders. Mixing with fresh binder increased the susceptibility to permanent deformation, while not improving the elastic properties. Different conclusions can be drawn from the analysis of binders recovered from the SMA11 mixture. In this case, the recovered binder, being a blend of PMB55 and A1, exhibits similar non-recoverable creep compliance to the A1 recovered binder but achieves higher elastic recovery. However, the obtained results are only at the threshold of the expected property range, similar to the PMB binder recovered from the SMA11 mixture without RAP. The properties of laboratory-prepared blends fall below the boundary curve and are shifted toward higher susceptibility to permanent deformation, with equal or slightly lower elastic recovery values.

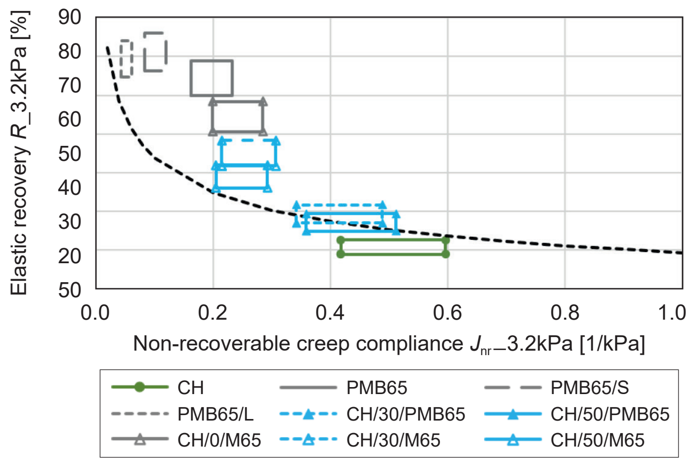


Fig. 8. MSCR test results of PMB65 and blends with binder recovered from CH RAP (95% confidence interval)

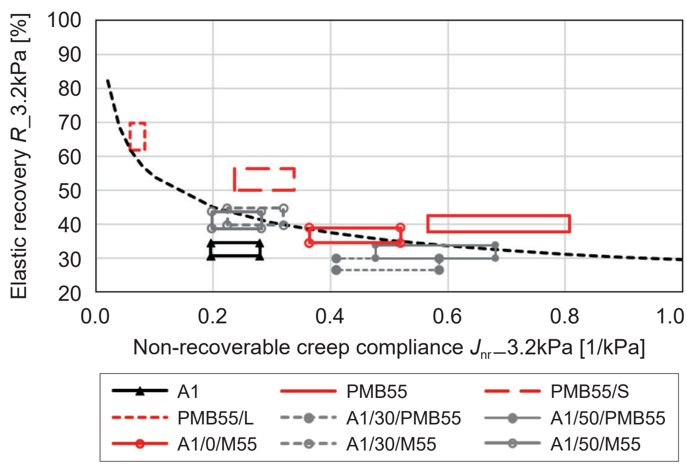


Fig. 9. MSCR test results of PMB55 and blends with binder recovered from A1 RAP (95% confidence interval)

## 4. SUMMARY AND CONCLUSIONS

As part of the study, an evaluation was carried out of binders recovered from SMA RAP originating from the milling of aged road surfaces, as well as their blends with fresh polymer-modified binders. The assessment of recovered binder properties compared with PMB 45/80-55 and PMB 45/80-65 demonstrated:

1. Advanced aging processes, evident in terms of consistency (penetration, softening point), low-temperature properties (Fraass breaking point), and elastic properties (elastic recovery in the ductilometer and under shear in MSCR).
2. However, it should be noted that the tests showed most results to be at a relatively good level, indicating suitability for reuse in new SMA mixtures. None of the binders exceeded the limiting values for penetration and softening point specified in PN-EN 13108-8.
3. The relatively weakest results were obtained for the Fraass breaking point; nevertheless, binder S7 met the requirements of PN-EN 14023 for unaged PMB 45/80-55 and PMB 45/80-65.
4. At the same time, the binders showed good elastic recovery, near the limits specified by the aforementioned standard.
5. MSCR rheological testing indicated very good properties for binder S7, while the other two showed weaker results compared to PMBs and fell below the boundary curve for favourable PMB properties.

Binders CH and A1, with the weakest properties, were selected for further investigation in order to evaluate whether blending with fresh binder could improve their performance. The study was carried out in two variants:

a) by laboratory blending of binders,

b) by recovery from SMA mixtures produced with CH and A1 RAP at *BR* values of 0%, 30%, and 50%.

Conducted tests of the blends showed:

1. A clear influence of the *BR* index on penetration results, which generally decreased with increasing aged binder content.
2. For the softening point, differences between the results were smaller and not conclusive: in the case of the CH binder, the softening point decreased, while for A1 it increased.
3. Nevertheless, it was evident that increasing the *BR* index shifted the results toward the values of binders recovered from A1 and CH RAP.
4. Fraass breaking point and elastic recovery tests, particularly for A1 blends, indicated a clearly positive effect of blending with fresh PMB. In most cases, especially at *BR* = 30%, the requirements of PN-EN 14023 for unaged PMBs were met.
5. In terms of MSCR results, CH blends at *BR* = 30% and 50% satisfied the required criteria. The results of A1 blends recovered from SMA mixtures with RAP also showed a positive effect of fresh binder, although the values remained below the MSCR boundary curve. In contrast, the blends of PMB55 and A1 prepared in the laboratory unexpectedly showed a deterioration of properties after blending with fresh binder.
6. In summary, the obtained results indicate that for CH and A1 RAP binders, *BR* = 30% can be considered a safe value in the context of binder properties. At higher levels, the use of rejuvenators should be considered. The properties of S7 RAP binder were sufficiently good to suggest no limitations on *BR* values and no need for rejuvenating additives. In every case, however, both the BR level and the need for recycling additives must ultimately be determined based on SMA mixture performance.

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# REFERENCES


[1] *Nicholls J.C.*, *Carswell I.*, *Widyatmoko I.*, *Elliott R.C.*, *Harris J.*, *Taylor R.*: Recycling surfacing materials back into thin surfacing systems. Proceedings of the Institution of Civil Engineers – Construction Materials, **161**, 3, 2008, 105-112, DOI: 10.1680/coma.2008.161.3.105

[2] *Kokken I.*, *Roberto A.*, *Hernando D.*, *Zaumanis M.*, *Hugener M.*, *Van den bergh W.*: Evaluating binder ageing and polymer degradation levels in different reclaimed asphalt pavement (RAP) fractions. Construction and Building Materials, **492**, 2025, Article ID: 142909, DOI: 10.1016/j.conbuildmat.2025.142909

[3] *Farid M.*, *Król J.*: Investigating the ageing process of polymer modified bitumen using a modified Thin-Film Oven Test in the aspect of recycling purpose. Roads and Bridges – Drogi i Mosty, **22**, 4, 2023, 379-386, DOI: 10.7409/rabdim.023.020

[4] *Szołtysik J.*, *Sorociak W.*, *Kwiecień S.*: Examination of the properties of asphalt mixtures consisting of reclaimed asphalt pavement with polymer modified binder and highly modified asphalt binder. Roads and Bridges – Drogi i Mosty, **23**, 1, 2024, 29-44, DOI: 10.7409/rabdim.024.002

[5] *Kandhal P.S.*, *Foo K.Y.*: Designing recycled hot mixture asphalt mixtures using superpave technology. National Center For Asphalt Paving Technology, NCAT Report No. 96-5, Auburn University, 1997, 7-22

[6] *Liphardt A.*, *Król J.*, *Radziszewski P.*: Influence of polymer modified binder content from RAP on stone mastic asphalt rutting resistance. Procedia Engineering, **153**, 2016, 407-413, DOI: 10.1016/j.proeng.2016.08.142

[7] *Blasl A.*, *Kraft J.*, *Lo Presti D.*, *Di Mino G.*, *Wellner F.*: Performance of asphalt mixes with high recycling rates for wearing layers. Proceedings of the 6th Eurasphalt Eurobitume Congress, Prague, Czech Republic, 2016, https://www.h-a-d.hr/pubfile.php?id=1137 (available: 03.09.2025)

[8] *Behnia B.*, *Dave E.V.*, *Ahmed S.*, *Buttlar W.G.*, Reis H.: Effects of recycled asphalt pavement amounts on low-temperature cracking performance of asphalt mixtures using acoustic emissions. Transportation Research Record, **2208**, 1, 2011, 64-71, DOI: 10.3141/2208-09

[9] *Eskandarsefat S.*, *Hofko B.*, *Sangiorgi C.*: A comparison study on low-temperature properties of Stone Mastic Asphalts modified with PmBs or modified fibres. International Journal of Pavement Engineering, **21**, 12, 2018, 1541-1549, DOI: 10.1080/10298436.2018.1554219

[10] *Yao Y.*, *Yang J.*, *Gao J.*, *Xu J.*, *Zhang Y.*, *Yu S.*: Effect of design parameters on low-temperature cracking resistance of recycled hot-mix asphalt mixtures. Materials and Structures, **58**, 24, 2025, DOI: 10.1617/s11527-024-02554-0

[11] *Ma T.*, *Mahmoud E.*, *Bahia H.U.*: Estimation of reclaimed asphalt pavement binder low-temperature properties without extraction: development of testing procedure. Transportation Research Record, **2179**, 1, 2010, 58-65, DOI: 10.3141/2179-07

[12] *Zhou Z.*, *Gu X.*, *Dong Q.*, *Ni F.*, *Jiang Y.*: Rutting and fatigue cracking performance of SBS-RAP blended binders with a rejuvenator. Construction and Building Materials, **203**, 2019, 294-303, DOI: 10.1016/j.conbuildmat.2019.01.119

[13] *Katla B.*, *Ravindra W.A.*, *Kota S.K.*, *Raju S.*: RAP-added SMA mixtures: How do fare? Journal of Materials in Civil Engineering, **33**, 8, 2021, Article ID: 04021199, DOI: 10.1061/(asce)mt.1943-5533.0003807

[14] *Bańkowski W.*: Evaluation of fatigue life of asphalt concrete mixtures with reclaimed asphalt pavement. Applied Sciences, **8**, 3, 2018, Article ID: 469, DOI: 10.3390/app8030469

[15] *Zaumanis M.*, *Mallick R.B.*: Review of very high-content reclaimed asphalt use in plant-produced pavements: state of the art. International Journal of Pavement Engineering, **16**, 1, 2015, 39-55, DOI: 10.1080/10298436.2014.893331

[16] *Gonçalves Luz P.M.S.*, *Silva I.M.*, *de Medeiros Melo Neto O.*, *Lucena Dias T.*, *de Figueiredo Lopes Lucena L.C.*, *Sampaio R.M.B.*: Analysis of the Degree of Blending (DoB) of recycled asphalt mixtures with variation in mixing temperature, type, and RAP content. Construction and Building Materials, **431**, 2024, Article ID: 136577, DOI: 10.1016/j.conbuildmat.2024.136577

[17] *Karlsson R.*, *Isacsson U.*: Material-related aspects of asphalt recycling – state-of-the-art. Journal of Materials in Civil Engineering, **18**, 1, 2006, 81-92,
DOI: 10.1061/(ASCE)0899-1561(2006)18:1(81)

[18] *Zia Alavi M.*, *Amani S.*, *Hosseinzadeh S.*: Evaluation of degree of blending and interaction between aged and virgin asphalt binders using rheological and fracture measurements, Case Studies in Construction Materials, **21**, 2024, Article ID: e03528, DOI: 10.1016/j.cscm.2024.e03528

[19] *Yang Y.*, *Wang C.*, *Yang Y.*: The progress of the interfacial diffusion between virgin and aged asphalt based on molecular dynamics simulation: A review. Processes, **11**, 10, 2023, Article ID: 3024, DOI: 10.3390/pr11103024

[20] *Xu P.*, *Zhang D.*, *Liu Z.*, *Wang F.*, *Luan D.*: Diffusion mechanism explorations on the sustainable warm mix asphalt and synchronous rejuvenated SBS-modified asphalt binder using the free volume theory. Sustainable Materials and Technologies, **41**, 2024, Article ID: e01061, DOI: 10.1016/j.susmat.2024.e01061

[21] *Li N.*, *Tang W.*, *Yu X.*, *Zhan H.*, *Wang X.*, *Wang Z.*: Laboratory investigation on blending process of reclaimed asphalt mixture. Construction and Building Materials. **325**, 2022, Article ID: 126793, DOI: 10.1016/j.conbuildmat.2022.126793

[22] *Zaumanis M.*, *Mallick R.B.*, *Poulikakos L.*, *Frank R.*: Influence of six rejuvenators on the performance properties of Reclaimed Asphalt Pavement (RAP) binder and 100% recycled asphalt mixtures. Construction and Building Materials, **71**, 2014, 538-550, DOI: 10.1016/j.conbuildmat.2014.08.073

[23] *Im S.*, *Zhou F.*, *Lee R.*, *Scullion T.*: Impacts of rejuvenators on performance and engineering properties of asphalt mixtures containing recycled materials. Construction and Building Materials, **53**, 2014, 596-603, DOI: 10.1016/j.conbuildmat.2013.12.025

[24] PN-EN 13108-8:2016-07 Bituminous mixtures – Material specifications – Part 8: Reclaimed asphalt

[25] PN-EN 12697-3:2013-10 Bituminous mixtures – Test methods for hot mix asphalt – Part 3: Bitumen recovery: Rotary evaporator

[26] PN-EN 1426:2025-02 Bitumen and bituminous binders – Determination of needle penetration

[27] PN-EN 1427:2015-08 Bitumen and bituminous binders – Determination of the softening point – Ring and Ball method

[28] PN-EN 13398:2017-12 Bitumen and bituminous binders – Determination of the elastic recovery of modified bitumen

[29] PN-EN 12593:2015-08 Bitumen and bituminous binders – Determination of the Fraass breaking point

[30] PN-EN 16659:2016-02 Bitumen and Bituminous Binders – Multiple Stress Creep and Recovery Test (MSCRT)

[31] *Mieczkowski P.*, *Budziński B.*, *Słowik M.*, *Kempa J.*, *Sorociak W.*: Experimental study of tensile properties of Styrene-Butadiene-Styrene modified asphalt binders. Materials, **14**, 7, 2021, Article ID: 1734, DOI: 10.3390/ma14071734

[32] *Nguyen Q.T.*, *Hoang T.T.N.*, *Bui X.C.*, *La V.C.*, *Tran T.K.D.*, *Nguyen Q.P.*, *Nguyen N.H.*: Mechanical properties of bitumen and asphalt mixture modified with polymer additives. Proceedings of the RILEM International Symposium on Bituminous Materials (ISBM 2020). Springer, Cham, RILEM Bookseries, **27**, 2022, 1321-1326, DOI: 10.1007/978-3-030-46455-4_168

[33] PN-EN 14023:2011 Bitumen and bituminous binders – Specification framework for polymer modified bitumens

[34] *Radziszewski P.*, *Sarnowski M.*, *Król J.*, *Pokorski P.*, *Jaskuła P.*, *Ryś D.*, *Pszczoła M.*: Low-temperature requirements for bitumen in Central East European road construction. The Baltic Journal of Road and Bridge Engineering, **14**, 2, 2019, 249-270, DOI: 10.7250/bjrbe.2019-14.442

[35] *Rys D.*, *Jaczewski M.*, *Pszczola M.*, *Jaskula P.*, *Bankowski W.*: Effect of bitumen characteristics obtained according to EN and Superpave specifications on asphalt mixture performance in low-temperature laboratory tests. Construction and Building Materials, **231**, 2020, Article ID: 117156, DOI: 10.1016/j.conbuildmat.2019.117156

[36] *D'Angelo J.*, *Kluttz R.*, *Dongré R.*, *Stephens K.*, *Zanzotto L.*: Revision of the Superpave high temperature binder specification: the multiple stress creep recovery test. Journal of the Association of Asphalt Paving Technologists, **76**, 2007, 123-162

[37] AASHTO TP 70-13 Multiple Stress Creep Recovery (MSCR) test of asphalt binder using a Dynamic Shear Rheometer (DSR). American Association of State Highway and Transportation Officials, 2013, https://img.antpedia.com/standard/files/pdfs_ora/20230616/AASHTO/AASHTO%20TP%207 (available: 03.09.2025)

[38] *Gajewski M.*, *Bańkowski W.*, *Gajewska B.*, *Sybilski D.*, *Horodecka R.*: Estimation of asphalt binders' resistance to permanent deformation with application of the MSCR and multiple shear creep long recovery (MSCLR) tests. Construction and Building Materials, **284**, 2021, Article ID: 122808, DOI: 10.1016/j.conbuildmat.2021.122808

[39] *Hossain Z.*, *Ghosh D.*, *Zaman M.*, *Hobson K.*: Use of the Multiple Stress Creep Recovery (MSCR) test method to characterize polymer-modified asphalt binders. Journal of Testing and Evaluation, **44**, 1, 2016, 507-520, DOI: 10.1520/JTE20140061

[40] *DuBois E.*, *Mehta Y.*, *Nolan A.*: Correlation between multiple stress creep recovery (MSCR) results and polymer modification of binder. Construction and Building Materials, **65**, 2014, 184-190, DOI: 10.1016/j.conbuildmat.2014.04.111

[41] *Bernier A.*, *Zofka A.*, *Yut I.*: Laboratory evaluation of rutting susceptibility of polymer-modified asphalt mixtures containing recycled pavements. Construction and Building Materials, **31**, 2012, 58-66, DOI: 10.1016/j.conbuildmat.2011.12.094

## Możliwość ponownego wykorzystania destruktu z warstw SMA: rozszerzona ocena właściwości odzyskanego polimeroasfaltu

**Streszczenie:** Artykuł przedstawia wyniki prac badawczych w zakresie oceny właściwości asfaltów odzyskanych z materiału powstałego w procesie frezowania warstw SMA na bazie polimeroasfaltów. Badania laboratoryjne przeprowadzono na asfaltach odzyskanych z RAP, na mieszaninach w ustalonych proporcjach ze świeżymi polimeroasfaltami oraz na lepiszczach odzyskanych z mieszanek SMA z granulatem asfaltowym. Zakres badań obejmował podstawowe badania klasyfikacyjne polimeroasfaltów oraz ocenę właściwości reologicznych metodą MSCR. Przeprowadzono analizę wyników, które pozwoliły ocenić stan lepiszczy odzyskanych i wybrać lepiszcza do badań na mieszaninach ze świeżymi PMB i granulaty do zaprojektowania mieszanek SMA z RAP. Analiza wyników mieszanin i lepiszczy odzyskanych pozwoliła na względną ocenę lepiszczy i wskazała na warianty, które potencjalnie mogą wymagać zastosowania dodatków regenerujących do recyklingu. Zaprezentowane badania są jednym z etapów badań realizowanych w ramach projektu badawczego rSMA2 dotyczącego recyklingu warstw SMA.

**Słowa kluczowe:** frezowina asfaltowa, lepiszcze asfaltowe, MSCR, recycling, SMA.