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Application of innovative bitumen for recycling in asphalt concrete containing reclaimed asphalt pavement

Abstract: Bitumen, as one of the oldest construction materials, has significant recycling potential, which makes it both environmentally friendly and in line with the principles of the circular economy. Although the recyclability of bituminous materials is widely recognised, the discussion continues on the possibility of increasing the efficiency of using Reclaimed Asphalt Pavement (RAP) in asphalt mixtures. The article presents the results of research on the application of a new type of experimental bituminous binder dedicated to recycling in asphalt concrete. The study included experimental tests of asphalt concrete for the binder course with variable RAP contents up to 30%, using a cold feeding process. Both laboratory test results and the findings from a trial road section are presented. For comparison, conventional road bitumen 35/50 was used as the reference binder, while an innovative recycling-dedicated binder 35/50 exp was applied as the experimental binder. The mixtures were subjected to classification testing as well as extended testing of long-term ageing resistance. The research confirmed that the experimental 35/50 exp bitumen, dedicated to recycling applications, enhances the compactability of mixtures containing 20-30% cold-feed RAP and improves the ageing resistance of asphalt mixtures. It was demonstrated that the action of experimental bitumen dedicated to recycling in mixtures containing RAP occurs in several stages: during production and laying, experimental bitumen supports compactability, while in the long term, it contributes to improved ageing resistance.

Keywords: ageing, bitumen, RAP, reclaimed asphalt pavement, recycling.

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1. INTRODUCTION

Asphalt mixtures are currently the most used material for road pavement construction. It is estimated that asphalt technology accounts for 90-95% of road construction materials worldwide. At the same time, in recent years, there has been growing interest in recycling asphalt pavements, driven by environmental protection needs, natural resource savings, and economic considerations. In many European countries, such as the Netherlands, the recovery rate of materials from pavement demolition reaches 100%, and the content of RAP in asphalt mixtures can reach up to 80% [1-3]. Practical experience shows that pavements built with recycled materials, when appropriate binders with increased ageing resistance and rejuvenating properties are used, do not lag behind pavements made solely from new materials in terms of performance. Additionally, their carbon footprint is estimated to be lower, mainly due to reduced exploitation of natural resources and decreased costs and emissions associated with material transport [4-6].

Bituminous material recycled from existing road pavements (site-won asphalt), after the appropriate processing and classification referred to as Reclaimed Asphalt Pavement (RAP), can be successfully reused in the construction of road pavement layers [7]. Asphalt recycling can be carried out at cold, warm, or hot temperatures, both directly on the rehabilitated road (using recyclers) and in asphalt mixing plants [8-10]. Introducing RAP in the form of granulated material into the mixing process allows control over the composition and properties of the mixtures [11, 12]. According to the latest recommendation by the General Directorate for National Roads and Motorways agency in Poland from 2018 as part of the RID-I project [13], three main categories of recycled asphalt material are distinguished in Polish terminology: site-won asphalt, reclaimed asphalt RA, and feedstock of reclaimed asphalt. This terminology was introduced following the update of PN-EN 13108-8 [14] and the RID-I research and development project. For simplicity, the term Reclaimed Asphalt Pavement (RAP) will be used for the purposes of this study.

One of the methods of introducing RAP into asphalt mixtures is the "cold feed" method, which involves adding the material at ambient temperature and moisture directly into the mixer [15]. The principle of this method is that hot aggregate transfers heat to RAP particles, allowing indirect heating and softening of the binder in the RAP [16]. This process, like the "hot" method, occurs without dedusting or fractionation of RAP. The method is particularly recommended for relatively low RAP contents and finer gradations. Its main advantage is technological simplicity - it does not require advanced and expensive investments in additional infrastructure (e.g., parallel drum) and can be implemented in older types of asphalt plants regardless of the contractor's operating scale. According to current experience, this technology allows effective dosing of 10% to 40% RAP relative to the mixture composition [17].

To achieve appropriate mechanical properties and performance of asphalt mixtures with RAP added directly to the mixer, the degree of mixture homogeneity and binder activation in RAP is crucial [15] [18-19]. Due to the partial activation of the old binder in RAP, it is recommended to use fresh binders with appropriate properties, preferably dedicated to recycling, which limit secondary ageing and support homogenisation and activation of the recycled material [20].

Introducing RAP into the asphalt mixture involves adding aged binder, characterised by higher stiffness and viscosity compared to fresh bitumen, which affects the mechanical properties of the mixture, particularly stiffness and cracking [21-22]. Ageing of bitumen is primarily driven by oxidation and changes in the colloidal structure, resulting in the progressive hardening of the binder. Recent studies have shown that certain modifiers can effectively inhibit these aging mechanisms by adding polyaniline nanofibers, which can reduce oxidation reactions and slow down aromatization, thereby enhancing the fatigue and rutting resistance of the binder [23]. Similarly, modern two-component polymer composites, particularly those containing NH_2 functional groups or chitosan-based components, have been found to reduce oxidation and improve long-term durability by limiting the progression of chemical ageing reactions [24]. An alternative approach involves the use of rejuvenators, which restore the viscoelastic balance of aged binders. Rejuvenated bitumens demonstrate lower aging susceptibility than virgin binders, and after full-service life, may even exhibit lower stiffness than untreated binders [25]. Innovative concepts also combine warm-mix technologies with bio-based rejuvenators, providing both reduced processing temperatures and improved chemical stability of aged binder blends [26]. Although rejuvenation can partially reverse

asphaltene aggregation induced by aging, the microstructure of aged bitumen cannot be completely recovered; yet its overall performance may remain within acceptable limits even after multiple aging-rejuvenation cycles [27]. Nevertheless, recent research indicates that some bio-recycled asphalt mixtures, despite promising binder-level rheological properties, may experience faster ageing rates than conventional mixtures, which highlights the need for further verification before full-scale implementation [28]. In summary, the recycling process is complex, and there are many ways to rejuvenate bitumen and limit aging, which is why it is also important to consider the interaction of materials. Achieving the desired volumetric and mechanical properties of asphalt mixtures in recycling technology requires ensuring the compatibility of RAP with other mixture components by promoting effective interaction of the fresh binder with the RAP particles. The conditions of site-won asphalt processing into reclaimed asphalt also significantly influence the effective use of binder and aggregate in asphalt mixtures. When planning mixture production in recycling technology, it is essential to ensure binder availability in RAP and estimate the mixability of recycled binder with fresh binder [29-31].

In Poland, a decade ago, the share of RAP in asphalt mixtures was negligible, typically limited to 10% cold-fed content [32]. This limitation was mainly due to contractors' lack of experience, plant technical limitations, lack of investor and road authorities' acceptance, legal barriers [33-34], and limited availability of suitable material. Currently, a clear trend of increasing RAP use in road construction and rehabilitation works is observed. With direct dosing of RAP into the mixer, a share of up to 30-40% recycled material in the new mixture is possible, provided appropriately selected binders with high compatibility and/or rejuvenators are used.

In response to technological and environmental challenges, Warsaw University of Technology, in cooperation with ORLEN S.A., developed an innovative bitumen specifically for mixtures containing RAP. The result of the R&D project was the creation and implementation of a new type of road bitumen named "exp bitumen" designed for recycling technology. Thanks to its rejuvenating and anti-ageing properties, the new bitumen allows the production of asphalt mixtures with up to 30% RAP cold-fed directly to the mixer, without compromising final mixture properties. The developed technology enables effective mixing of recycled material with fresh aggregate and binder, ensuring the proper workability and durability of the mixture. The new experimental bitumen was designed considering material compatibility, structural homogeneity, and appropriate adhesive and cohesive properties in the finished mixture.

The overall objective of the project was to develop a new bitumen dedicated specifically to asphalt recycling technology, enabling higher RAP utilisation while maintaining or improving mixture performance. This strategic goal reflects the growing need for environmentally responsible road construction solutions and the optimisation of natural resource use. The aim of the study presented in this paper is to compare selected results obtained during laboratory research with those achieved during the implementation of the developed technology on a full-scale trial pavement section. Consequently, this article presents an insightful case study that illustrates the transition from laboratory-scale research to practical field application in road construction.

2. MATERIALS AND METHODS

2.1. MATERIALS

Binder course asphalt concrete (AC) mixtures were designed for binder courses (W) with medium traffic load category (KR 3-4) and maximum aggregate size of 16 mm, containing 0%, 20%, and 30% RAP with road bitumen 35/50 and new experimental bitumen for recycling 35/50 (exp). For mixtures with 20% and 30% of RAP, the gradation curves were designed separately to match as closely as possible the reference mixture without RAP and to ensure void content within ±0.5% of the reference mixture.

The composition of binder course asphalt concrete was designed based on analysis of mineral aggregate gradations and control points specified in WT-2 2014. Reference mixtures (35/50 ref) were optimised for air-void content, water resistance, and rutting resistance to meet the national requirements. In all mixtures, the binder was then replaced with experimental bitumen (35/50 exp), and the full testing cycle was conducted to compare the influence of binder type on mixture properties. Mixture compositions, binder content, and RAP content are shown in Table 1, and gradation curves in Fig. 1.

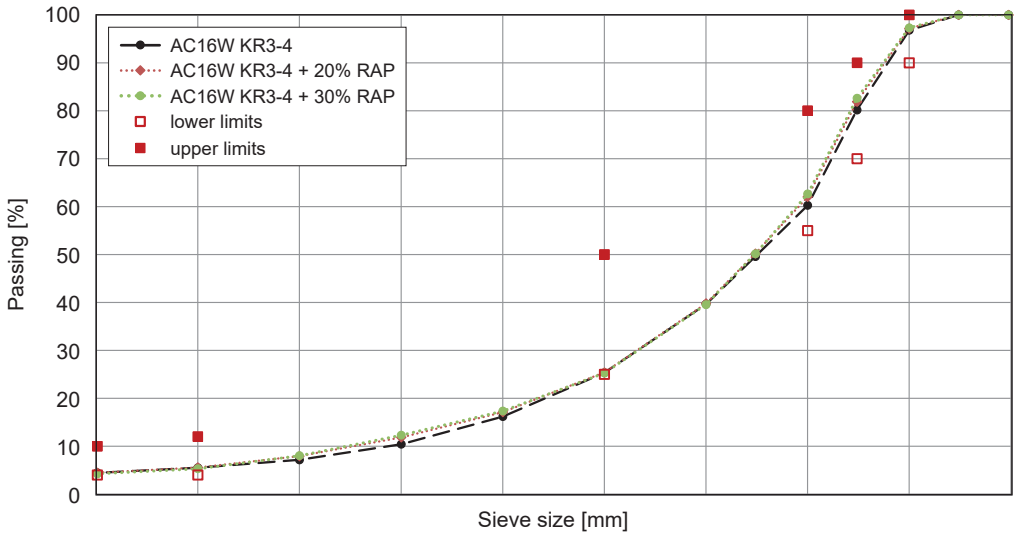

Fig. 1. Gradation curves of asphalt mixtures with varying RAP content

Table 1. Composition of the laboratory-designed mixtures with varying RAP content

Materials / Properties	Asphalt mixture and RAP content		
	AC16W KR3-4 35/50		
	0% RAP	20% RAP	30% RAP
Total binder content [%]	4.4	4.4	4.4
Filler [%]	3.8	1.4	0.0
Fine aggregate [%]	19.1	10.5	6.2
Coarse aggregate [%]	72.7	64.5	60.7
RAP [%]	0.0	19.1	28.7
Bitumen 35/50 [%]	4.4	3.4	2.9
Bitumen from RAP [%]	0.0	1.0	1.5
Binder replacement [%]	0.0	22	33

The gradation curves presented in Fig. 1 exhibit that all mixtures fall within the required control points. Table 1 shows that as the RAP content increased, the proportions of filler and fine aggregate were gradually reduced. The total binder content was maintained at 4.4%, and as the RAP content increased, the binder replacement index rose. For 30% RAP, the replacement index was 33%, which is higher than the RAP content percentage due to the higher average binder content in RAP than assumed in the target mixture.

For the laboratory tests, RAP originating from the combined milling of the asphalt concrete surface and binder layers was used. The material came from the milling of the runway at the Okęcie Airport in Warsaw. The RAP was granulated and classified based on its homogeneity. The density of the granulated RAP, calculated as the average of five samples, was 2.865 g/cm^3. The properties of the binder recovered from the RAP were also determined. The penetration of the recovered binder at 25°C was 35 [0.1 mm], and the softening point determined using the Ring and Ball method was 67°C.

The RAP used for the road experimental sections had a maximum particle size of 16 mm and an average density of 2.651 g/cm^3. Extraction testing showed that the predominant aggregate in the RAP was basalt, at 70%. The average binder content was 5.9%, with the penetration of the recovered binder at 25°C being 20 [0.1 mm]. The softening point, determined using the Ring and Ball method, was 69.2°C.

2.2. TESTING METHODS

Basic volumetric properties, such as bulk density and air void content, were tested for all AC16W mixtures. Both series, using road bitumen 35/50 and experimental bitumen 35/50 exp, had identical mixing, conditioning, and compaction procedures. The aggregate was preheated to 210°C, ensuring proper temperature conditions for effective binder coating and for RAP indirect preheating. The mixing process consisted of two stages: dry mixing, during which the heated aggregate and RAP were mechanically blended for 15-20 seconds, followed by wet mixing, during which the binder was added, and the mixture was blended until the aggregate was fully coated, typically taking approximately 1 minute. Samples were compacted from the ready-made mixture at 135 ± 5°C using

a Marshall hammer, according to PN-EN 12697-8, with 75 blows applied on each side.

Water resistance was tested according to PN-EN 12697-12 and conditions given in Annex 1 to WT-2 2014 recommendation. The indirect tensile strength ratio *ITSR* was determined as the ratio of the tensile strength of wet samples to dry samples. For each set of dry and wet samples, five *ITS* strength repetitions were performed on separate samples. Indirect tensile strength *ITS* at 10°C was also measured, corresponding to the linear viscoelastic range of most asphalt mixtures. Cylindrical samples of 150 mm diameter and 45 ± 1 mm height were compacted in a gyratory compactor to the reference density from Marshall compaction. Four samples per mixture were tested. Loading was applied at a rate of 50 ± 2 mm/min until failure.

The assessment of ageing resistance was conducted using the procedure specified in the AASHTO R30-02 standard "Mixture Conditioning of Hot-Mix Asphalt (HMA)", which describes the conditions for conditioning compacted asphalt mixture specimens to determine long-term ageing (LTOA). For preliminary short-term ageing (STOA) and to adapt the procedure to Polish conditions, the short-term conditioning method for asphalt mixtures, as provided in Technical Guidelines WT-2 2014, Annex 2, was applied prior to specimen compaction. For the conditioned specimens, the ageing index of asphalt mixtures after STOA was determined according to the WT-2 2014, Annex 2 method, as well as for specimens subjected to LTOA using the AASHTO method.

For the ageing tests, the mixture was pre-heated for 2 hours at 135 ± 5°C prior to specimen compaction. The mixture was thoroughly mixed before compaction. Subsequently, following the LTOA procedure, the compacted asphalt mixture specimens were conditioned at 85 ± 1°C for 5 days in a forced-air oven. The long-term ageing index ΔS_{LTOA} of the asphalt mixture was calculated using the formula (1):

$$\Delta S_{LTOA} = \frac{ITCY_{LTOA}}{ITCY_{oryg,WT-2}} \quad (1)$$

where:

$ITCY_{LTOA}$ – stiffness modulus of the asphalt mixture after LTOA ageing,

$ITCY_{oryg,WT-2}$ – stiffness modulus of the asphalt mixture before ageing, conditioned according to WT-2.

The ageing index can take a value greater than, equal to, or less than one, which can be interpreted as follows: $\Delta S > 1$ – stiffening due to ageing, $\Delta S = 1$ – no change in properties due to ageing, $\Delta S = 1$ – softening due to ageing.

3. LABORATORY STAGE RESULTS

Proper compaction of the asphalt mixture to the target volumetric density is a fundamental criterion in designing the composition of reference mixtures and is also used during the acceptance of asphalt layers to calculate the compaction index. To determine the effect of the 35/50 exp bitumen on the compactability of mixtures with an increased content of reclaimed asphalt pavement (RAP), mixtures with experimental bitumen 35/50 exp were not optimised in comparison to the reference mixtures with 35/50 road bitumen. In all tests, the principle was to replace only the bitumen from 35/50 to 35/50 exp while maintaining the same mineral composition specified in Table 1. A summary of the volumetric densities of AC16W KR3-4 asphalt mixtures with varying RAP contents, using reference 35/50 bitumen and experimental 35/50 exp bitumen, is presented in Fig. 2.

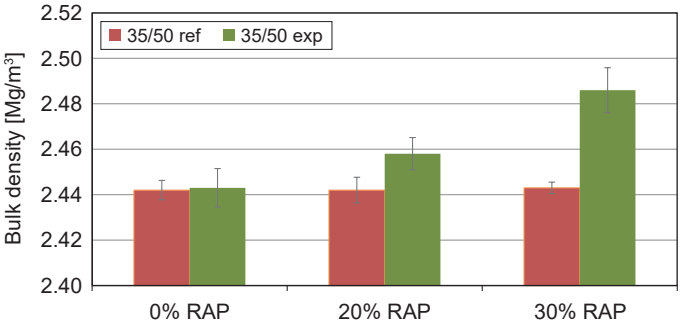

Fig. 2. Bulk density of AC16W asphalt mixtures

Comparing the volumetric density levels obtained for the various mixtures, it can be observed that the reference mixtures exhibit comparable volumetric densities. In contrast, mixtures with 35/50 exp bitumen exhibit a noticeable increase in volumetric density as the RAP content rises. It can be assumed that experimental bitumen contributes to greater homogeneity of the mixture as well as improved internal lubricity during compaction.

It is worth noting that in engineering practice, reclaimed asphalt pavement often originates from different batches and/or stockpiles, which may require the development of a new mix design or updating a type test. In the analysed case, no significant limitations were identified regarding

the possibility of designing asphalt concrete mixtures with typical RAP obtained from the combined milling of two asphalt layers. However, it was observed that as the RAP content in the mixture increases, the ability to compaction rises for mixtures with 35/50 exp bitumen, in contrast to mixtures with conventional 35/50 road bitumen, where the density remains at a comparable level (Fig. 2). Considering this phenomenon and the use of the same aggregates, RAP and composition in the reference mixtures as in the experimental mixtures, the conclusions tend to state that it is the effect of the experimental binder used, rather than the addition of RAP.

Another important property to consider when evaluating road pavement performance, as well as the use of recycled materials, is the water resistance of the asphalt mixture. In Poland, the level of requirements for water resistance depends on the pavement layer in which the mixture is to be placed, rather than on the type of mixture. For the binder course, a minimum *ITSR* ratio value of 80% is required. It should be noted that adequate water resistance, including freeze–thaw cycles, constitutes a critical criterion in Poland when designing the mixture composition. A summary of the water and frost resistance of AC16W KR3-4 asphalt mixtures with varying RAP contents and experimental (exp) bitumen is presented in Fig. 3.

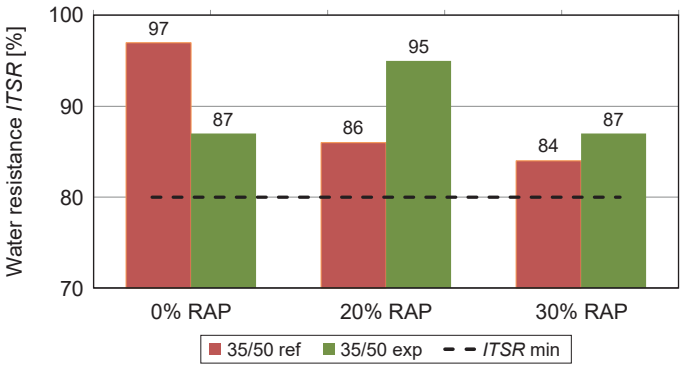

Fig. 3. Water resistance of AC16W asphalt mixtures according to the ITSR method

Comparing the water resistance levels across the different mixtures, it can be concluded that it is possible to design AC16W asphalt concrete with up to 30% cold-dosed RAP content that meets the required criteria, both with conventional and experimental bitumen. All AC16W mixtures fulfilled the requirements specified in Technical Guidelines WT-2 2014.

Analysing the *ITSR* values of reference AC16W mixtures with varying RAP content reveals that water resistance gradually decreases as the RAP content in the mixture increases. In the case of the reference mixture without RAP, a very favourable *ITSR* value of 97% was obtained, whereas for the mixture containing 30% RAP, the *ITSR* value decreased to 84%. It should be emphasised that, from a regulatory perspective, this value is still considered safe and continues to meet the requirements of WT-2 2014.

For most of the experimental mixtures, it can be noted that the use of experimental bitumen reduces their sensitivity to changes in RAP content. Moreover, the better performance of mixtures with 35/50 exp bitumen over the reference mixtures becomes evident at higher RAP contents of 20-30%. The lower water resistance of mixtures with experimental bitumen compared to reference mixtures without RAP is most likely due to the lower viscosity of experimental bitumen and the ITSR testing methodology, where the internal cohesion of the mixture, governed by the bitumen consistency, plays a key role during indirect tensile loading to failure.

Therefore, the beneficial properties of the experimental bitumen are particularly evident in mixtures with increased RAP content, where conditions for effective interaction between the bitumens are met. This results in greater mobilization of the bitumen in the RAP, enhancing the homogeneity of the bitumen layers (fresh bitumen and bitumen in RAP) within the mixture.

Another key property determining the success of effective asphalt pavement recycling is resistance to ageing, as it governs the long-term durability of the mixture in the road pavement. Additionally, it should be noted that Reclaimed Asphalt Pavement (RAP) already contains aged bitumen, making it advisable to limit further ageing or to rejuvenate the aged binder.

Ageing resistance under laboratory conditions can be assessed by simulating an accelerated stiffening process of the mixture at elevated temperatures in the presence of oxygen from the air. Fig. 4 presents the results of the long-term ageing *LTOA* index for AC16W mixtures, calculated based on stiffness modulus measurements using the IT-CY method at 10°C.

Comparing the values of the ΔS_{LTOA} ageing indices of the mixtures, it can be observed that the positive values indicate a stiffening of the mixtures due to the combined effect of temperature and air exposure. For the reference

mixtures AC16W (ref), the ageing index values average 1.24. In the case of mixtures with experimental bitumen, the ageing indices average 1.08. This suggests that, despite the overall increase in mixture stiffness resulting from the addition of higher amounts of RAP and the ageing process, the rate of this process is lower than in reference mixtures with conventional road bitumen. Comparing the two groups of mixtures, it can be concluded that the experimental bitumen exhibits anti-ageing behaviour, which is consistent with the expected functionality of this binder designed for recycling applications.

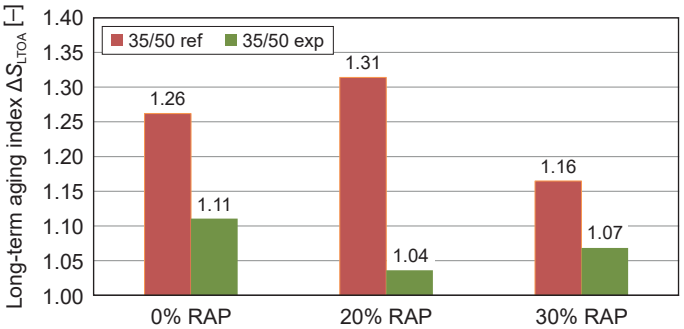

Fig. 4. Long-term aging index of AC16W asphalt mixtures at 10°C

4. APPLICATION AND RESULTS ON ROAD EXPERIMENTAL SECTIONS

As part of the development work of the project, a new type of experimental binder was tested under industrial production conditions, and an experimental road pavement was constructed. The test section is in Januszowice, in the Słomniki municipality, along road No. 1173K. The total length of the test section was 1,210 meters, and it was divided into three segments: one reference section with 35/50 binder and two experimental sections with an increased amount of reclaimed asphalt pavement (30% w/w RAP). In one of the experimental sections, the 35/50 exp binder was used. The configuration of the individual road sections, including the reference and experimental segments, is illustrated schematically in Fig. 5, while Fig. 6 presents photographs of the construction of the respective sections.

As part of the 35/50 exp bitumen testing, the road section was constructed with a binder layer of AC 16 asphalt concrete in three variants:

- AC 16 W 35/50 asphalt concrete with 20% RAP content, adopted as the reference section and representing the standard solution used by the road construction company,
- AC 16 W 35/50 asphalt concrete with 30% RAP content, adopted as Experimental Section I,
- AC 16 W 35/50 exp asphalt concrete with 30% RAP content and the experimental binder, adopted as Experimental Section II.

Reference Section	Experimental Section I	Experimental Section II
AC 16 W **35/50** 20% RAP	AC 16 W **35/50** 30% RAP	AC 16 W **35/50 exp** 30% RAP
from 8+700 to 9+120 km	from 8+292 to 8+700 km	from 7+850 to 8+292 km

Fig. 5. Outline of the experimental sections with a binder course layer

Fig. 6. Experimental section: a) existing pavement condition before milling, b) paving of the reference mixture AC16W 35/50 with 20% RA, c) paving of the experimental mixture AC16W 35/50 exp with 30% RA

For research purposes, samples were taken at the plant (COLAS Skawina) directly during the production of the asphalt mixture. Representative loose mixture samples were collected in 10 kg portions into specially prepared and labelled paper bags to ensure effective mixture identification and streamline the preparation of samples for laboratory testing. At each sampling, the mixture temperature was recorded, and its homogeneity was assessed macroscopically.

A summary of the water resistance of the asphalt mixtures produced at the asphalt plant is presented in Fig. 7.

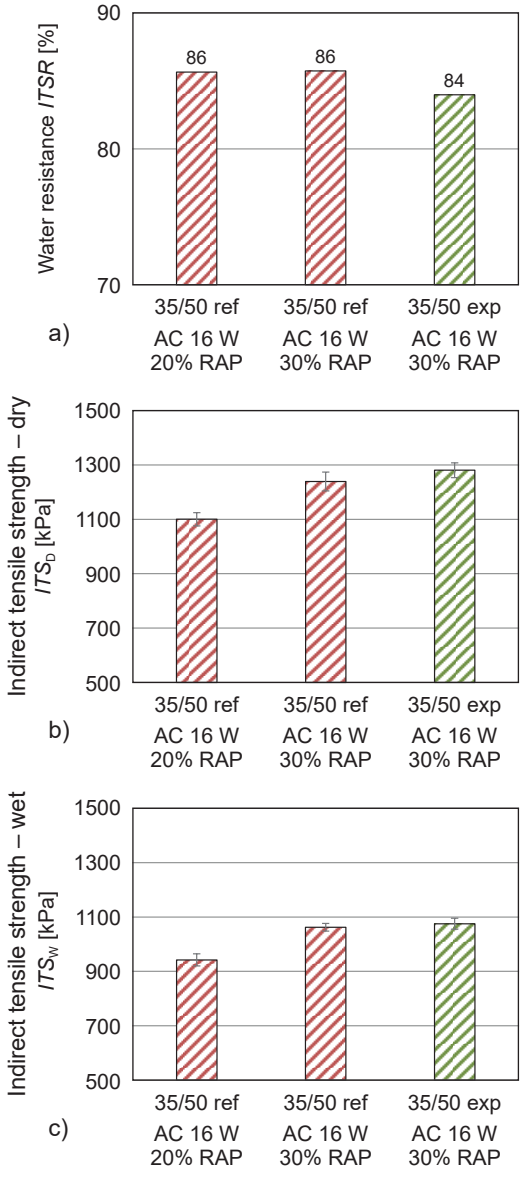

Fig. 7. Water resistance of AC16W asphalt mixtures plant-produced for experimental section: a) *ITSR* ratio, b) indirect tensile strength – dry, c) indirect tensile strength – wet

Based on the analysis of water sensitivity test results, it was found that all the analysed AC16W binder layer mixtures met the water sensitivity requirement, achieving *ITSR* values above the required 80% threshold (Fig. 7a).

Analysing the detailed results of the indirect tensile strength ITS tests (Figs 7b and 7c), which form the basis for calculating the *ITSR* ratio, it can be observed that in both dry samples (Fig. 7b) and wet samples (Fig. 7c), an increase in the asphalt granulate content by 10% compared to the reference mixture with 20% GA leads to an increase in tensile strength. In the case of the mixture with 35/50 exp bitumen, it can additionally be noted that the tensile strength is the highest, which may indicate better homogenization of the experimental bitumen layer with the binder in the RAP.

The aging resistance of the plant-produced mixture was also examined, as it is a fundamental factor determining the durability of the asphalt mixture, and was confirmed for experimental binders during laboratory tests. For each sample of the production mixture, the stiffness modulus was first measured using the IT-CY method, assuming that the production mixture had already undergone technological aging, corresponding to the STOA method in laboratory testing. The results of the stiffness modulus tests at 13°C are presented in Fig. 8. The testing temperature, higher than that used in laboratory tests, was chosen to provide results for the verification of the pavement structure design.

Stiffness modulus results of the mixtures after short-term (technological) aging (Fig. 8a) showed that the highest stiffness (13,017 MPa) was observed for the AC16W asphalt concrete mixture for the binder layer with conventional 35/50 road bitumen and 30% RAP content. For the same type of mixture with 35/50 exp bitumen, a slightly lower stiffness of 12,489 MPa was obtained. The lowest stiffness (12,000 MPa) was recorded for the reference asphalt concrete mixture, which had a 20% lower RAP content.

Analysis of IT-CY stiffness test results for mixtures subjected to long-term aging LTOA indicated that the mixtures exhibited some stiffening after LTOA, while the relative stiffness trends among the different mixtures were maintained. Similar to the short-term ageing results, the reference mixture with 35/50 road bitumen and 20% RAP content showed the lowest stiffness. AC16W mixtures with 30% granulate content and either 35/50 or 35/50 exp road asphalt achieved stiffness values of 13,742 MPa and 13,038 MPa, respectively, after LTOA.

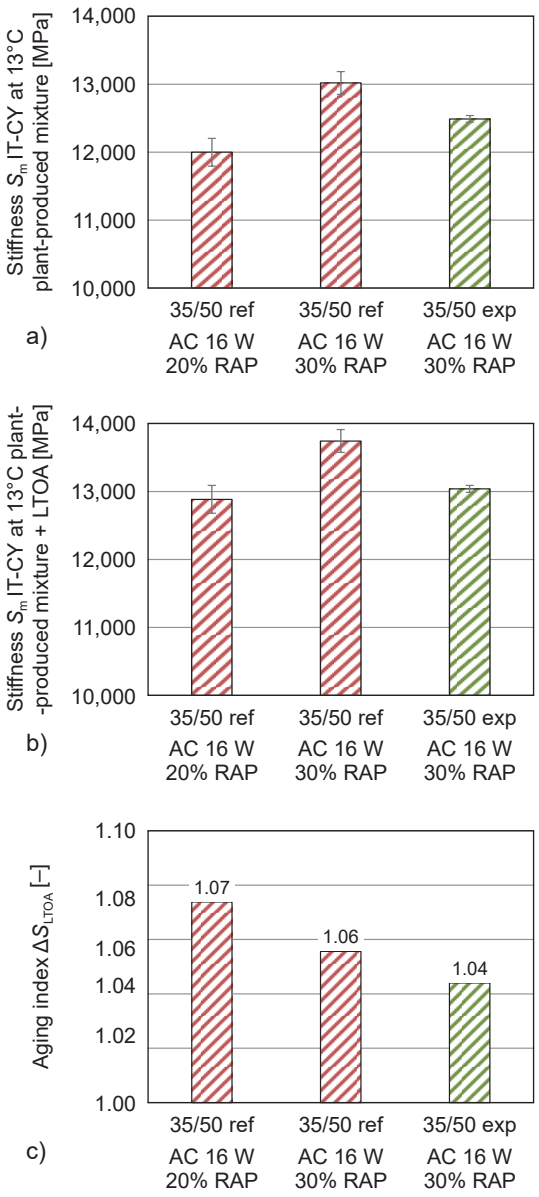

Fig. 8. Stiffness and aging resistance of plant-produced asphalt mixtures for experimental section: a) stiffness at 13°C, b) stiffness at 13°C after LTOA aging, c) aging index ΔS_{LTOA}

The assessment of mixture stiffness separately is insufficient when aiming to determine the aging resistance of a given asphalt mixture. A key aspect of this evaluation is calculating how much the stiffness modulus has changed as a result of the aging process compared to the mixture before aging. Analysing the calculated aging index values (Fig. 8c) for the individual asphalt mixtures showed that the greatest stiffening occurred in the reference section AC16W 20% GRA asphalt concrete mixtures (ΔS_{LTOA} = 1.07), where conventional 35/50 bitumen was used and, due to the lower RAP content, proportionally more fresh binder was present. Conversely, the lowest, most favourable aging index was observed for the AC16W mixture with 35/50 exp bitumen (ΔS_{LTOA} = 1.04).

It should be noted that the aging resistance was confirmed at the industrial production scale, and the aging index value for the mixture with 35/50 exp bitumen is lower than that of mixtures with conventional 35/50 bitumen. This result is highly favourable, confirming the anti-aging and rejuvenating properties of the new experimental binder.

5. CONCLUSIONS

Based on the conducted research, it was concluded that:

1. The reclaimed asphalt (RAP) used in the study, obtained from the combined milling of surface and binder layers, allows for the correct design of asphalt mixtures, both with the experimental binder and with conventional road bitumen.
2. The implementation of experimental sections and industrial-scale production confirmed the conclusions from the laboratory phase, showing that the new type of experimental binder effectively supports the recycling process, particularly for a mixture containing 30% of RAP cold-feeding added directly into the mixer.
3. Specifically, it was found that the experimental 35/50 exp bitumen improves the compactability of mixtures at higher cold-feed RAP contents of 20-30%.
4. All tested asphalt mixtures with 35/50 exp bitumen demonstrated good water resistance at a stable level above the required limit (>80%), both in laboratory tests and during asphalt plant-level production, confirming the good performance of the experimental bitumen.
5. A key parameter and advantage of the new experimental technology is its enhanced resistance to aging.
6. Despite the general increase in stiffness of all tested mixtures due to higher RA content and the ongoing aging process, the rate of this process is lower for experimental technology than for mixtures with conventional road bitumen.
7. Comparing the two groups of mixtures, it can be concluded that the experimental bitumen demonstrates anti-aging properties, consistent with the intended functionality of this binder in recycling technology.

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Zastosowanie innowacyjnego asfaltu drogowego do recyklingu w betonie asfaltowym z granulatem asfaltowym

Streszczenie: Materiał asfaltowy jako jeden z najstarszych materiałów budowlanych ma olbrzymi potencjał do recyklingu, przez co jest materiałem ekologicznym i spełniającym wymagania gospodarki obiegu zamkniętego. Możliwość recyklingu materiałów asfaltowych jest powszechnie znana, ale wciąż toczy się dyskusja na temat możliwości zwiększenia efektywności zastosowania granulatu asfaltowego w mieszankach asfaltowych. W artykule przedstawiono wyniki badań nad zastosowaniem nowego eksperymentalnego lepiszcza asfaltowego do recyklingu betonu asfaltowego. Zakres artykuł obejmuje badania eksperymentalne mieszanki typu beton asfaltowy do warstwy wiążącej ze zmienną zawartością granulatu asfaltowego do 30% dozowanego na zimno. Przestawiono wyniki z fazy badań laboratoryjnych oraz testowania technologii na drogowym odcinku doświadczalnym. Do mieszanek jako lepiszcze referencyjne zastosowano asfalt drogowy 35/50 oraz jako lepiszcze eksperymentalne asfalt drogowy do recyklingu 35/50 exp. Mieszanki poddano wszechstronnym badaniom w zakresie właściwości klasyfikacyjnych, jak również rozszerzonym badaniom odporności na starzenie długoterminowe. Wyniki badań pokazały, że eksperymentalne lepiszcze asfaltowe 35/50 exp dedykowane do technologii recyklingu poprawia odporność mieszanek mineralno-asfaltowych na starzenie oraz wspomaga ujednorodnienie dwóch warstw lepiszczy. Stwierdzono, że oddziaływanie nowego lepiszcza w mieszankach mineralno-asfaltowych z granulatem asfaltowym jest wieloetapowe. Podczas produkcji i wbudowania mieszanek z asfaltem w technologii eksperymentalnej następuje większa aktywacja i homogenizacja lepiszcza z granulatu asfaltowego poprzez asfalt eksperymentalny, natomiast w ramach oddziaływania długofalowego następuje poprawa odporności starzeniowej.

Słowa kluczowe: asfalt, GRA, granulat asfaltowy, recykling, starzenie.