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EVALUATION OF THE FEASIBILITY OF INCORPORATING HIGHER RAP MATERIALS CONTENT IN ASPHALT CONCRETE WITH THE USE OF ADDITIVES THAT IMPROVE THE WORKABILITY OF ASPHALT MIXTURES

OCENA MOŻLIWOŚCI STOSOWANIA ZWIĘKSZONEJ ZAWARTOŚCI GRANULATU ASFALTOWEGO W BETONIE ASFALTOWYM Z WYKORZYSTANIEM DODATKÓW POPRAWIAJĄCYCH URABIALNOŚĆ MIESZANEK MINERALNO-ASFALTOWYCH

STRESZCZENIE. Recykling materiałowy ze względu na ochronę środowiska, zrównoważony rozwój odgrywa coraz większe znaczenie w budowie nawierzchni drogowych. Szczególnie dotyczy to zastosowania destruktu asfaltowego do warstw konstrukcyjnych nawierzchni. Jednym z problemów występujących przy stosowaniu większych ilości destruktu asfaltowego w mieszankach mineralno-asfaltowych jest pogorszenie ich urabialności i jednorodności szczególnie w przypadku dozowania granulatu asfaltowego na zimno. Artykuł zawiera wyniki badań nad zastosowaniem dodatków poprawiających urabialność betonu asfaltowego do warstwy podbudowy ze zwiększonym do 40% dodatkiem granulatu asfaltowego dozowanym w technologii na zimno. W badaniach zastosowano dodatki parafin F-T, upłynniaczy pochodzenia roślinnego oraz zeolitów, które miały na celu poprawę homogeniczności i zagęszczalności mieszanek przy zastosowaniu obniżonych temperatur wbudowania. Przeprowadzono ocenę zagęszczalności mieszanek z różną zawartością granulatu asfaltowego przy zastosowaniu 3 rodzajów dodatków poprawiających urabialność. Zagęszczalność oceniano na podstawie analizy przebiegu zagęszczania w prasie żyratorowej, określając m.in. wymaganą ilość cykli do uzyskania wymaganego zagęszczenia, a także naprężenia ścinające oraz wskaźnik zagęszczenia w funkcji ilości cykli zagęszczania. W dalszej kolejności mieszanki mineralno-asfaltowe poddano badaniom w celu weryfikacji ich odporności na deformacje trwałe oraz działanie wody. Na podstawie wyników badań i analiz wykazano, że istnieje możliwość stosowania zwiększonej zawartości granulatu asfaltowego w warstwach podbudowy z betonu asfaltowego zarówno w standardowych, jak i obniżonych temperaturach wbudowania dzięki zastosowaniu dodatków poprawiających urabialność i zagęszczalność mieszanek.

SŁOWA KLUCZOWE: recykling, granulat asfaltowy, urabialność, zagęszczalność, beton asfaltowy, zeolity, parafiny F-T.

ABSTRACT. The material recycling due to the environmental protection and sustainable development is playing an increasingly important role in the road pavement construction. This is especially true for the use of reclaimed asphalt pavement (RAP) materials for the pavement construction layers. One of the problems encountered in the use of larger quantities of the RAP in asphalt mixtures is the deterioration of their workability and homogeneity especially in the case of cold dosing of RAP. The paper reports the results of a study on the use of additives to improve the workability of asphalt concrete for the subbase layer with an increase of up to 40% in crushed RAP content, dosed in the cold technology. In the study, additives of the F-T waxes, plant-derived liquefiers and zeolites were used to improve homogeneity and compactability of the mixtures using reduced paving temperatures. An evaluation of the compactability of mixtures with different contents of the RAP, using 3 types of additives to improve workability, was carried out. Compactability was evaluated by the compaction analysis in a gyratory compactor, determining, among other things, the required number of cycles to achieve the required compaction, as well as the shear stress and compaction index as a function of the number of compaction cycles. Subsequently, the asphalt mixtures were tested to verify their resistance to permanent deformation and resistance to water. Based on the results of the research and analysis, it was shown that it is possible to use increased RAP materials content in asphalt concrete base layers at both standard and reduced paving temperatures, through the use of additives that improve the workability and compactability of the mixtures.

KEYWORDS: asphalt concrete, compactability, reclaimed asphalt pavement (RAP), recycling, workability, zeolites, F-T waxs.

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1. INTRODUCTION

One of the basic elements of sustainable transportation development is road construction, which includes the construction of new and reconstruction of existing roads, as well as their maintenance using recycled materials from used road construction layers.

As a result of studies conducted for many years in Poland and around the world on the reuse of waste materials for the production of asphalt mixtures, it has been found that potentially the greatest use in the construction of the upper structural layers of road pavements is primarily found in the form of the crushed RAP materials [1–5]. In the countries of the European Union, including Germany, France, Belgium, the Netherlands, the use of RAP for pavement construction currently reaches 80% [6, 7]. In Poland, according to the current technical documents [8], it is permissible to use the addition of RAP only for the binder and base course. Also, the content of RAP in the asphalt mixture must not exceed 20% for the "cold" dosing method and 30% for the "hot" method. These requirements significantly limit the full use of the potential of this technology, especially in terms of meeting the principles of environmental protection and sustainable development. For this reason, research is being carried out at the Warsaw University of Technology to recycle asphalt pavements using the highest possible content of RAP in new mixtures. In addition, in order to strengthen the economic effect of the technology, the cold method of dosing asphalt granulate, i.e., without preheating, was assumed. This avoids the need for an additional drum, the so-called "black drum" that is a part of the cyclic asphalt mix plant, which allows the RAP to be heated before being combined with the new components during mix production. The production of mixtures with hot dosing of RAP is not yet widespread in Poland at the moment [9, 10], due to the small number of plants adapted to this technology.

One of the technological problems occurring with the use of larger amounts of RAP in asphalt mixtures is the deterioration of their workability and homogeneity, especially in the case of cold dosing of RAP. This results in a deterioration of the compactability of the mixtures and the layers made from them, which consequently reduces the durability of the pavement [3, 11].

Previous experience with the production of Warm Mix Asphalt (WMA) technology shows that, in addition to effectively reducing technological temperatures [12, 13], improvements in the workability of asphalt mixtures are also achieved. Improvements in the workability of asphalt mixtures can be achieved both by using various types of additives that reduce the viscosity of bitumen and by taking advantage of the phenomenon of bitumen foaming with water [14–17]. The most commonly used additives in the WMA technology include:

- zeolite additives (minerals included in the silicate group) of natural or synthetically produced origin,
- organic additives that reduce the viscosity of the bitumen (e.g., the Fischer-Tropsch synthetic wax – Sasobit),
- chemical additives that reduce the surface tension of the bitumen (e.g., the Rediset and Evotherm adhesive agents).

In addition, the results of many years of research conducted at the Warsaw University of Technology, in the field of WMA technology [16, 18], confirm that the workability of -asphalt mixtures is also affected by additives of plant origin (bioflux).

The combination of additives to improve the workability of the mixture and increased RAP content makes it possible, on the one hand, to reduce the heat emission into the atmosphere as a result of the cold dosing of the RAP, and on the other hand, to manage a large amount of recycled material.

Within the framework of the Research Program for the Development of Road Innovations, titled "The Use of Recycled Materials", (RID-I-6) [19], extensive laboratory testing of binders and asphalt mixtures was carried out, based on which the possibility of applying increased RAP content to the asphalt mixture in WMA technology using the aforementioned additives was determined. The research carried out in this regard was primarily aimed at developing methods of designing and producing asphalt mixtures in such a way that, after proper consideration of the properties of the RAP, with the increased content of its application, it is possible to obtain mixtures that meet the requirements in terms of stiffness, fatigue performance, resistance to permanent deformation, thermal cracking and water resistance.

This paper analyzes the effects of three workability-enhancing additives on the compactability of asphalt concrete for the base layer (AC P) containing the RAP materials with an increased content of up to 40%, added by means of the cold technology. Compactability was evaluated by analyzing the results of asphalt concrete volumetric density tests, and the effectiveness of the additives improving the workability of the AC mixture was controlled by determining its resistance to permanent deformation and to the effects of water and frost.

2. AIM AND SCOPE OF THE STUDY

The purpose of the study was to evaluate the feasibility of manufacturing and paving an asphalt mixture with an increased content of the cold-dosed RAP through the use of additives that improve the workability of the mixture.

Three asphalt concrete mixtures for the AC 22 P base layer were analyzed, with 0%, 20%, and 40% of the RAP. Moreover, 3 types of additives were used in the mixtures to improve the workability of the asphalt mixtures, including the F-T wax, zeolite and a plant-derived liquefier. It was assumed that by using the additives, it would be possible to produce a homogeneous mixture with an increased content of the RAP compared to the typical contents used in the cold dosing of RAP.

For each mixture and for each type of additive, the compactability tests in the gyratory compactor were performed, and resistance to permanent deformation and resistance to water and frost were determined to verify performance properties.

3. TEST MATERIALS

Three asphalt concrete mixtures designed for KR3-4 traffic load category were tested: AC_0RAP, AC_20RAP, and AC_40RAP. The mixes contained 0%, 20%, and 40% of the RAP in the mineral mixture, obtained from milling the binder and wearing layers (AC S + AC W). The compositions of the mixtures are given in Table 1. The asphalt mixtures were designed based on the 2014 WT-2 guidelines, selecting the proportions of virgin aggregates in such a way that all 3 mixtures were characterized by the most similar ordinates of particle size distribution curves.

Table 2 shows the basic properties of binders – the PMB 25/55-60 virgin binder and the binder recovered from the RAP.

The binder recovered from the RAP had significantly lower penetration and elastic recovery compared to the virgin PMB 25/55-60 polymer modified bitumen, indicating a significant degree of aging and the absence or negligible level of polymer modification. In terms of softening point and viscosity, the two binders showed no significant differences.

Table 1. Compositions of asphalt mixtures tested

Component	Content [% relative to asphalt mixture]		
	AC_0RAP	AC_20RAP	AC_40RAP
PMB 25/55-60 binder	3.9	2.9	1.9
filler – limestone powder	4.8	3.8	0.0
washed fine aggregate 0/2 (limestone)	14.4	5.8	0.0
coarse aggregate 2/8 (limestone)	24.0	15.4	7.7
coarse aggregate 8/16 (limestone)	24.0	23.1	21.1
coarse aggregate 16/22 (limestone)	28.8	28.8	28.8
RAP from AC S + AC W	0.0	19.2	38.4
binder from RAP (BR indicator)	0.0 (0)	1.0 (25)	2.0 (50%)
Adhesive additive	0.4 (relative to the bitumen)	0.4 (relative to the bitumen)	0.4 (relative to the bitumen)

Table 2. Basic properties of the virgin and recovered binder from the RAP

Property	PMB 25/55-60	Asphalt recovered from the RAP
Penetration [0.1 mm]	44	16
Softening point [°C]	65.8	68.5
Elastic recovery [%]	76	38
Dynamic viscosity at 90°C [Pa·s]	104.9	116.6
Dynamic viscosity at 110°C [Pa·s]	12.6	13.8
Dynamic viscosity at 135°C [Pa·s]	1.8	2.0

The following additives were also used in the study to improve the workability of the mixtures in technological processes:

- the F-T wax in the amount of 3% by weight of binder,
- zeolite in an amount of 0.3% by weight of the asphalt mixture,
- bio-flux in an amount of 2.5% by weight of binder (according to the Patent No. PL 214138 B1).

4. RESEARCH METHODOLOGY

4.1. PREPARATION OF SAMPLES

Samples of asphalt mixtures were produced in the laboratory using the following component dosing temperatures:

- the PMB 25/55-60 binder – 165°C,
- virgin aggregate – 210°C,
- RAP – 25°C.

The prepared mixtures were then thermostated to the assumed compaction temperatures, i.e., a typical temperature of 150°C and a reduced temperature of 110°C.

Due to the different contents of the RAP (0, 20, 40%) and additives used (no additive, F-T wax, zeolite, bioflux), the samples were marked as follows:

- without additive _0RAP, without additive _20RAP, without additive _40RAP,
- wax F-T_0RAP, wax F-T_20RAP, wax F-T_40RAP,
- zeolite_0RAP, zeolite _20RAP, zeolite _40RAP,
- bioflux_0RAP, bioflux_20RAP, bioflux_40RAP.

4.2. COMPACTABILITY TEST

Compactability was evaluated by analyzing the compaction process in a gyratory compactor.

The reference bulk density was determined in accordance with the EN 12697-6 on samples compacted in a Marshall hammer. The resulting bulk densities (Table 3) were taken as reference densities for further compaction analyses conducted in a gyratory compactor.

Table 3. Summary of reference bulk densities

Determination of asphalt mixture	Bulk density [Mg/m^3]	Density [Mg/m^3]	Air void content [%]
AC_0RAP	2.398	2.542	5.7
AC_20RAP	2.386	2.561	6.8
AC_40RAP	2.423	2.581	6.1

Compaction of samples in the gyratory compactor was carried out for all mixtures until the compactor made 200 revolutions in order to capture the moment when the mixture reached the standard bulk density, for each of the additives and at each of the RAP content. Compaction of all mixtures was carried out under the same conditions, applying a pressure equal to 0.6 MPa and selecting the mass of the sample so that at the end of the compaction process a sample with a height of 120 ±3 mm was obtained.

The assessment of compaction susceptibility, indirectly characterizing the workability of the mixture, was carried out on the basis of the analysis of curves of the increase in bulk density as a function of the number of compaction cycles. The gyratory compactor used made it possible to record the bulk density of the compacted mixture in successive cycles (rotations) of compaction. In addition, shear stresses were measured during the compaction of the samples. On the basis of the obtained curves of density change as a function of the number of cycles, the number of revolutions necessary to obtain a density equal to the reference bulk density was determined. The compaction index of samples prepared in a gyratory compactor was also determined as the ratio of the bulk density in a given compaction cycle to the reference bulk density determined on the Marshall's samples.

4.3. TEST OF RESISTANCE TO PERMANENT DEFORMATION

Resistance to permanent deformation was tested in a small wheel tracking apparatus, in air according to the standard procedure. Samples for resistance to permanent deformation, measuring 315x315x60 mm, were prepared in a rolling device. All samples for the rutting test were compacted until a compaction index of 98–100% was achieved. Testing of each mixture was performed on two parallel samples. The test mixtures were thermostated for one hour after sample preparation and before the start of compaction to the assumed compaction onset temperatures of 150°C and 110°C. Previously, the prepared mixtures were stored at 135°C for 2 hours. The total time of thermostatting the mixture before compaction was 3 hours. Based on the results of the rutting test, the values of the proportional rut depth PRD_{air} and the wheel tracking slope WTS_{air} were determined.

4.4. WATER RESISTANCE TESTING

Water resistance was evaluated according to the procedure described in Annex 1 of the 2014 WT-2 guidelines. The test specimens were prepared in a Marshall hammer using 2x35 strokes per side of the specimen. The test mixtures were thermostated for one hour after being made and before starting compaction to the assumed compaction onset temperatures of 150°C and 110°C. In order to determine the ITSR index, 5 water-conditioned and 5 reference specimens were subjected to indirect tensile strength testing by determining ITSw and ITSd parameters, respectively.

5. RESEARCH RESULTS

5.1. RESULTS OF COMPACTABILITY TESTS IN A GYRATORY COMPACTOR OF MIXTURES WITH RAP

Fig. 1 and 2 show curves describing the increase in the bulk density of compacted asphalt mixtures over successive compaction cycles in a gyratory compactor. Fig. 1 shows the curves for mixtures with three RAP contents and three different additives compacted at 150°C, while Fig. 2 shows them at 110°C. The figures also show the level of reference bulk density and bulk density values corresponding to the minimum and maximum content of air voids in the asphalt mixture according to the requirements of WT-2 of 2014.

Analyzing the course of the bulk density growth curves shown in Fig. 1 and 2, it can be concluded that in most of the cases analyzed, the fastest favorable bulk density growth is characterized by asphalt mixtures with the addition of zeolite. Particularly noteworthy is also the addition of bioflux, which also significantly accelerated the increase in bulk density of the compacted -asphalt mixtures. As expected for each of the mixtures tested with 0%, 20%, and 40% of RAP, the slowest density growth is characterized by mixtures without additives that improve workability. Therefore, it can be concluded that the use of all analyzed additives in both mixtures with and without RAP, compacted at standard and reduced temperatures, has a positive effect on improving the workability and compactability of the mixtures. Based on the analysis of Fig. 1 and 2, it can also be concluded that among the analyzed additives, the F-T wax has the lowest effectiveness in improving workability. A comparison of the results from Fig. 1 and 2 shows that the compaction temperature affects the compactability of asphalt mixtures, while the effectiveness of the tested additives at both 150°C and 110°C is comparable.

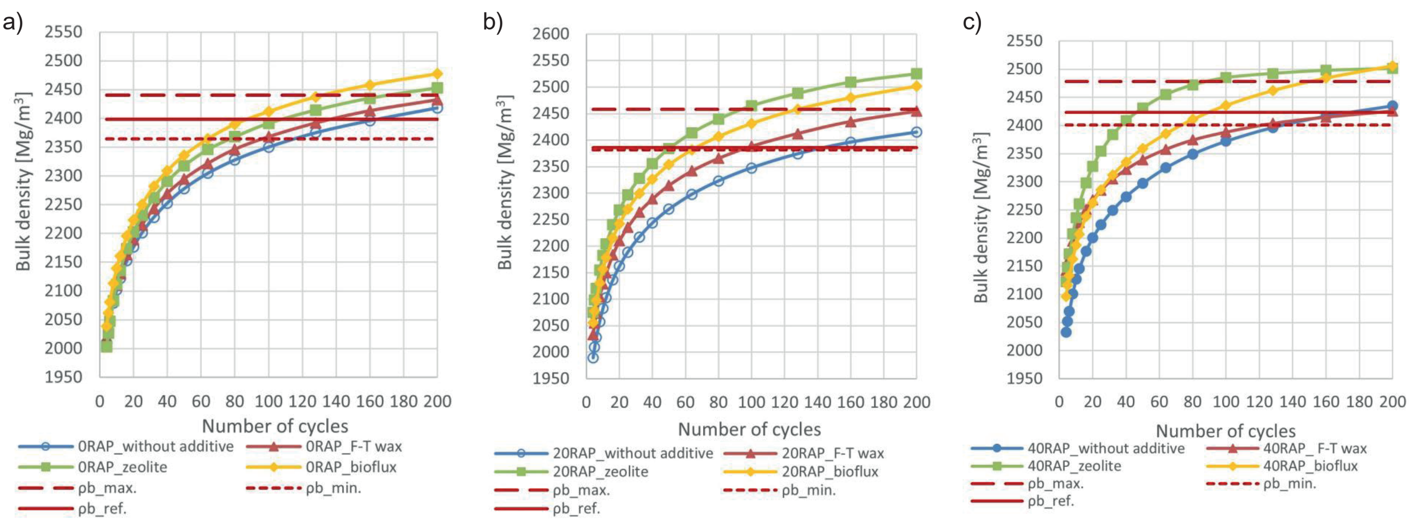

Fig. 1. Dependence of the bulk density on the number of compaction cycles at 150°C: a) AC22P_0RAP, b) AC22P_20RAP, c) AC22P_40RAP

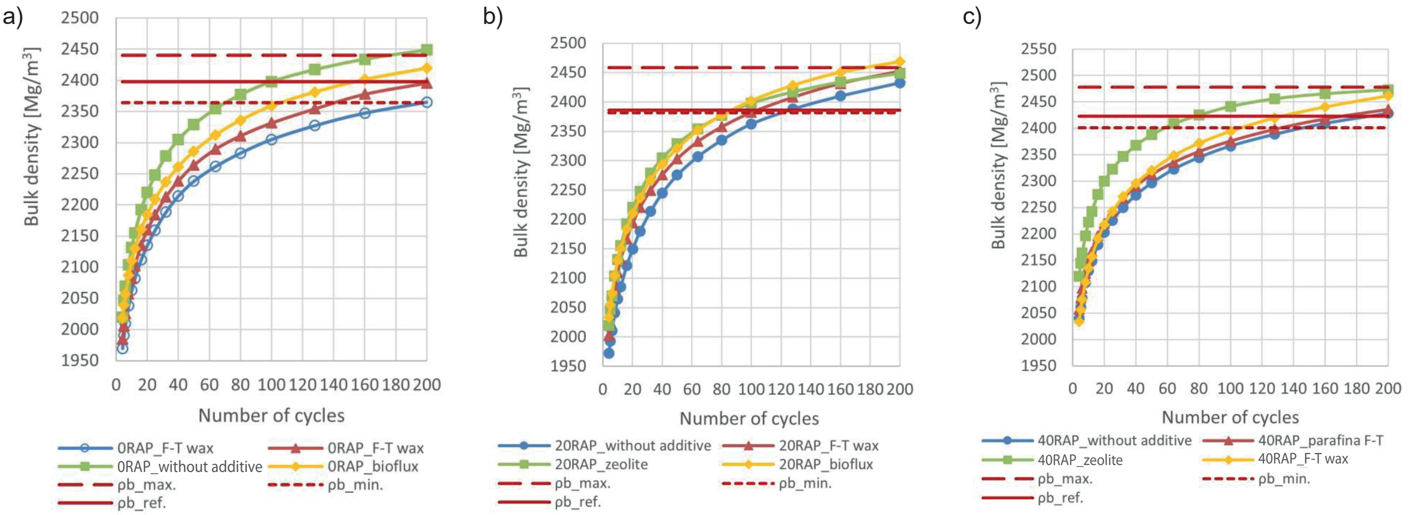

Fig. 2. Dependence of the bulk density on the number of compaction cycles at 110°C: a) AC22P_0RAP, b) AC22P_20RAP, c) AC22P_40RAP

Fig. 3 and 4 show the values of shear stresses measured in successive compaction cycles as a function of the compaction index determined in successive compaction cycles of asphalt mixtures.

Analyzing the dependence of shear stress on the compaction index, shown in Fig. 3 and 4, it can be concluded that the dependence for the most results have a course close to linear. However, in the case of the use of some additives, especially zeolite, there is an inflection of the graph, which can be interpreted as an increase in susceptibility to compaction after obtaining a compaction index close to 1. This behavior of mixtures with zeolite additives confirms, on the one hand, the effectiveness of this type of additive in improving the workability of the mixture, but at the same time indicates that mixtures with this additive may be susceptible to over-compaction. The behavior of mixtures with zeolite additives can be explained by the phenomenon of micro-foaming of the binder, which is characteristic of this type of additive. The other additives tested, i.e., the F-T wax and a plant-derived liquefier, cause a reduction in the viscosity of the bitumen due to other physical and chemical phenomena occurring directly in the binder but not changing its structure.

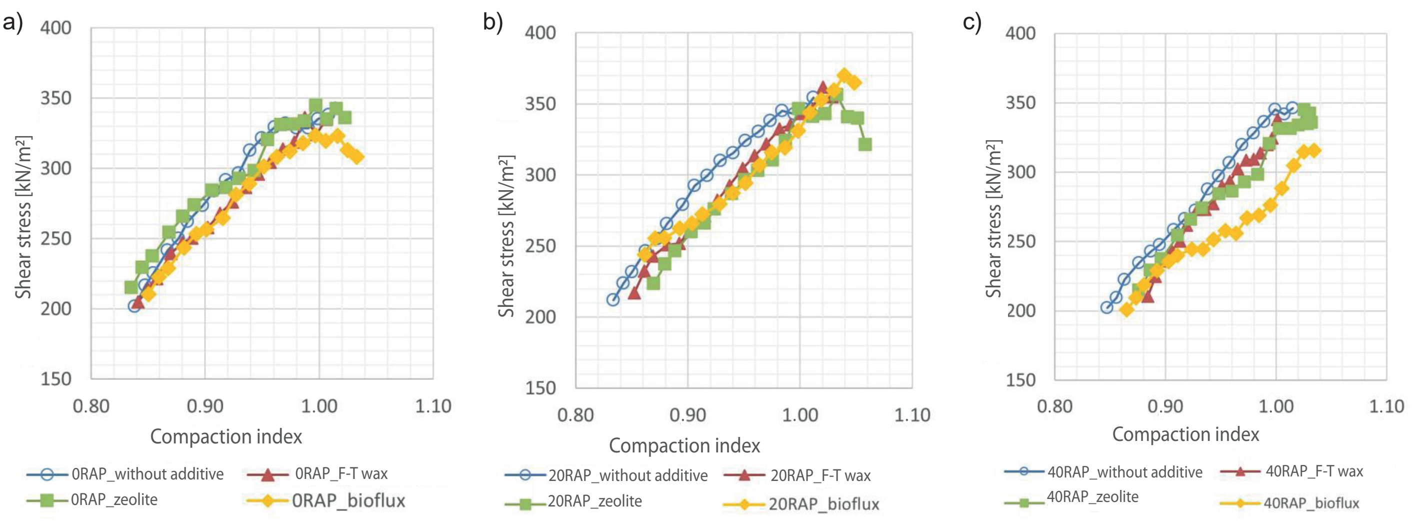

Fig. 3. Dependence of shear stress on the compaction index of AC22P mixtures compacted at 150°C: a) AC22P_0RAP, b) AC22P_20RAP, c) AC22P_40RAP

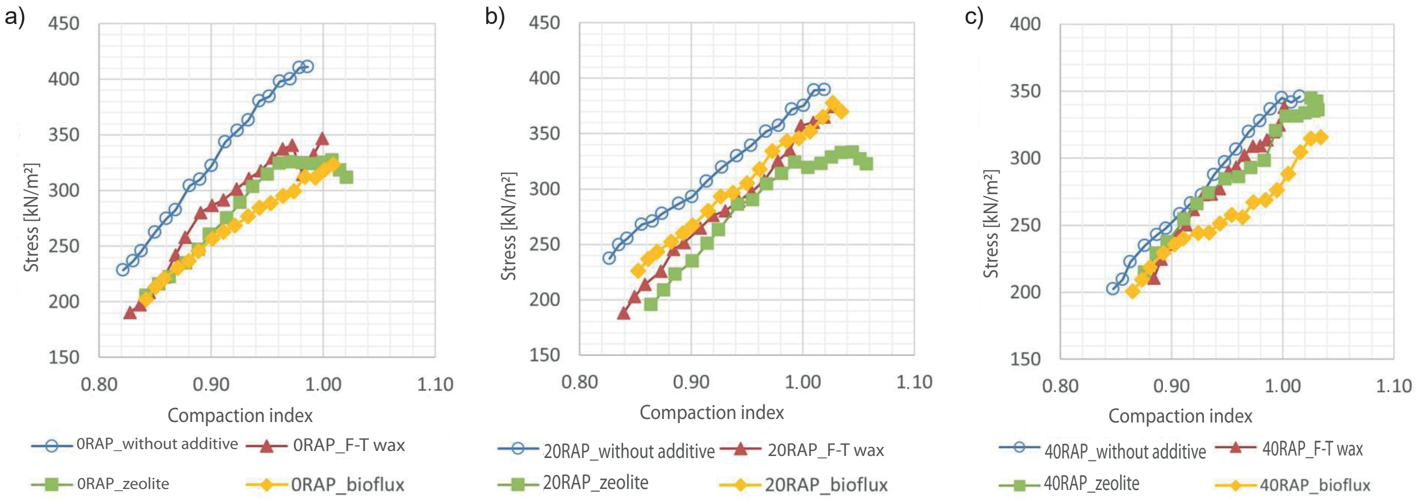

Fig. 4. Dependence of shear stress on the compaction index of AC22P mixtures compacted at 110°C: a) AC22P_0RAP, b) AC22P_20RAP, c) AC22P_40RAP

In Fig. 3 and 4 it can also be seen that the highest stress values occur in all analyzed cases in mixtures without additives, which confirms the validity of using the analyzed additives to improve workability. The lowest stress values in the vast majority of cases occur for mixtures in which bioflux additive was used. In addition, most of the presented stress-compaction index relationships are characterized by a near-parallel course for each of the analyzed additives. The exception to this is the mix with zero RAP and no additives, which is characterized by a significantly faster increase in stress during compaction compared to the other mixes.

Based on the determined bulk density values for successive compaction cycles, the required number of cycles (rotations) to obtain the reference bulk densities shown in Table 3 was determined for each mixture, each additive and the two compaction temperatures. A summary of the determined number of cycles for the mixtures compacted at 150°C is shown in Fig. 5, while for the mixtures compacted at 110°C it is shown in Fig. 6.

Analyzing the number of cycles required to achieve the reference bulk density at 150°C, it can be concluded that the longest compaction process was required for mixtures produced without additives to improve workability (from 144 to 172 cycles), regardless of the content of RAP. Among mixtures without additives, the most compaction cycles were achieved for a mixture with a RAP content of 40% m/m. Of the additives analyzed to achieve the required compaction of mixtures with the RAP at 150°C, the zeolite additive was the most effective (51 cycles for a mixture with 20% RAP content and 46 cycles for a mixture with 40% RAP content, respectively). The second most effective was the addition of bioflux (67 and 89 cycles, respectively) and the third was the addition of the F-T wax (97 and 108 cycles, respectively). At the same time, it should be noted that when zeolite was used, the mixture without RAP required twice as many cycles to achieve the reference density as the mixes with 20% and 40% of RAP. This may be due to the lower virgin binder content of the mixtures with 20% and 40% of RAP, which is more susceptible to zeolite than the RAP binder. Therefore, with the same zeolite content in all mixtures,

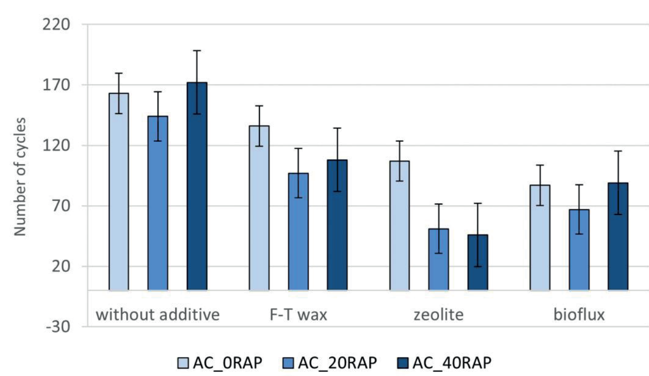

Fig. 5. Summary of the number of compaction cycleswat 150°C in a gyratory compactor required to obtain the reference bulk density

the micro-foaming process may have occurred more efficiently in the mixtures with a higher zeolite/virgin binder ratio. A similar but less pronounced effect could be observed for mixtures with the F-T wax, for which the mixture without RAP also required more compaction cycles. Only in the case of the bioflux additive were no significant differences observed between the numbers of cycles required to achieve the reference density at different RAP contents. This may indicate that bioflux has a greater effect on the binder contained in the RAP, which was also demonstrated in earlier work [20].

Comparing the test results summarized in Fig. 5 and 6, it can be concluded that, as a result of the 40°C reduction in the compaction temperature, the number of cycles required to obtain the reference bulk density at 110°C is on average from about 28 cycles higher than for mixtures compacted at 150°C, with the greatest difference observed for a mixture with 40% of RAP. For all three additives, mixes with the RAP content of 40% required the highest unfavorable number of cycles. This can be explained by the significant negative effect of the high content of aged RAP on the workability and compactability of the mixture at lower temperatures as well as the lower effectiveness of the effects of the tested additives.

As in the case of mixtures compacted at 150°C, zeolite was also the most effective additive at 110°C, the second most effective was bioflux and the third was the F-T wax. In addition, for all the additives analyzed, as well as for the mixture without the workability-enhancing additive, the mixture with 20% of RAP showed the shortest compaction at 110°C. It should be noted that the smallest differences between mixtures with different RAP contents compacted at 150°C and 110°C occurred when zeolite was applied.

The lower number of cycles required to compact a mix with 20% of the RAP (at both 150°C and 110°C) is to be explained by the different grain composition of this mix compared to the others as well as the highest level of free spaces achieved for the reference mix without additives, which then translates into the volumetric properties of the mixtures with additives.

5.2. TEST RESULTS FOR RESISTANCE TO PERMANENT DEFORMATION

In order to verify the fulfillment of the requirements for resistance to permanent deformation of mixtures with individual additives, a rutting test was carried out in accordance with the PN-EN 12697-22. Fig. 7–10 illustrate the results of the permanent deformation test carried out on the asphalt mixtures. Fig. 7 and 8 show the obtained values of the proportional rut depth PRD_{air} for mixtures compacted at 150°C and 110°C, respectively. Fig. 9 and 10 show the obtained values of the wheel tracking slope WTS_{air} for mixtures compacted at 150°C and 110°C, respectively. The figures indicate the maximum permissible values of the PRD and WTS parameters for the KR3-4 traffic load category according to the 2014 WT-2 requirements.

Analyzing the proportional rut depth values shown in Fig. 7 and 8, it can be concluded that all of the analyzed mixtures, regardless of the content of RAP as well as the type of additive used, met the requirements for the

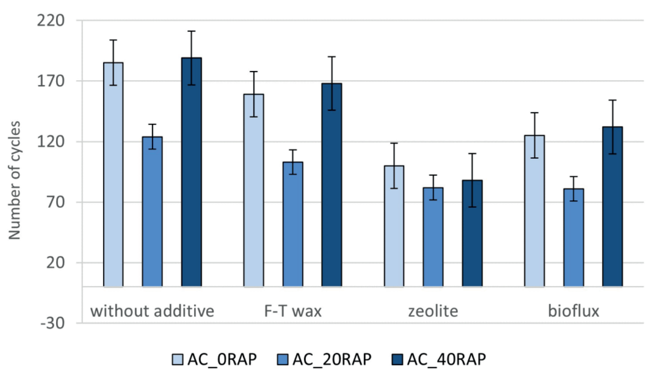

Fig. 6. Summary of the number of compaction cycles at 110°C in a gyratory compactor s required to obtain the reference bulk density

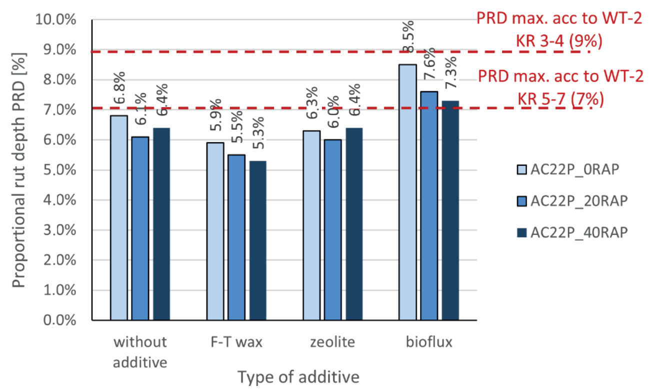

Fig. 7. Summary of obtained values of the proportional rut depth PRD_{air} for mixtures compacted at 150°C

base layer mixtures for traffic load category KR3-4, as specified in the 2014 WT-2 document. In addition, most of the analyzed mixtures, with the exception of those in which the bioflux additive was used, also meet the requirements for the higher traffic load category KR5-7. It can be concluded that among the analyzed additives, the bioflux additive has the least favorable effect on resistance to permanent deformation, for which the obtained values of the PRD_{air} parameter are the highest. This effect applies to both mixtures compacted at the standard temperature of 150°C and the reduced temperature of 110°C, and is due to the liquefaction properties characteristic of the bioflux additive. In contrast, the lowest values of the PRD_{air} parameter were obtained for mixtures with the Fisher-Tropsh wax additives. This effect is characteristic of F-T wax additives, which at high operating temperatures cause an increase in the stiffness of the asphalt binder, which translates into an increase in the resistance to permanent deformation of mineral-asphalt mixtures with these additives. Mixtures with zeolite additives, in turn, are characterized by values of the PRD_{air} parameter similar to those obtained for mixtures without additives. Thus, it can be concluded that zeolite additives do not show a clear negative or positive effect on the change of proportional rut depth.

Based on the analysis of the obtained values of the wheel tracking slope shown in Fig. 9 and 10, it can be concluded that, as in the case of the PRD_{air} parameter, all of the tested mixtures met the requirements for the WTS_{air} parameter for asphalt mixtures intended for the base layer for the KR3-4 traffic load category. In addition, most of the analyzed mixtures also met the requirements as for the KR5-7 traffic load category. In the case of asphalt mixtures compacted at 150°C, the lowest values of the WTS_{air} parameter were obtained with the F-T wax and zeolite additives, while for mixtures compacted at 110°C, the lowest values were obtained for mixtures with zeolite additives and slightly higher for mixtures with the F-T wax additives. For both compaction temperatures, the highest values for the wheel tracking slope were obtained for mixtures containing the bioflux additive.

In conclusion, it can be said that with regard to the resistance of the asphalt mixture to permanent deformation, the most favorable effect was obtained with the addition of zeolite and F-T wax. In the case of the use of an additive in the form of bioflux, however, there may be a risk of deterioration of resistance to permanent deformation, however, as shown, mixtures with this additive by a large margin met the requirements for a base layer with an average traffic load category of KR3-4.

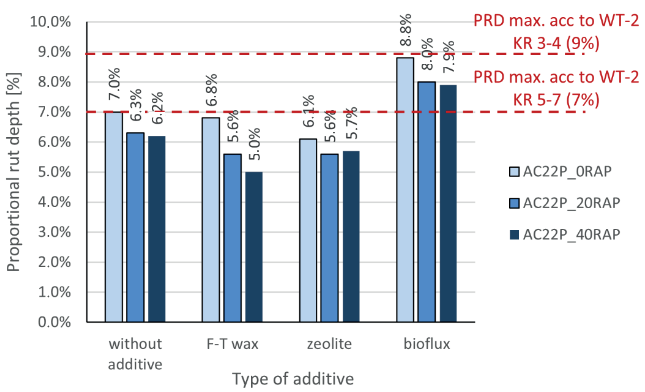

Fig. 8. Summary of obtained values of the proportional rut depth PRD_{air} for mixtures compacted at 110°C

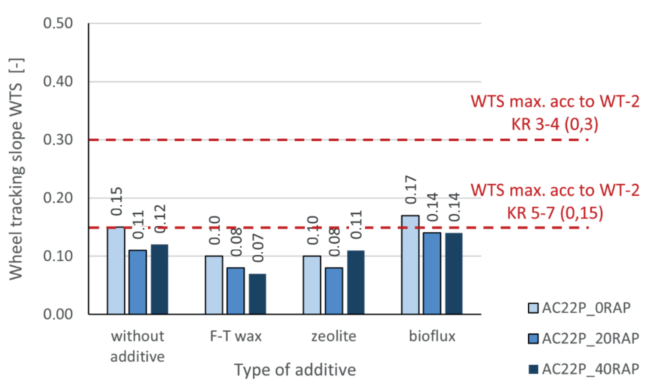

Fig. 9. Summary of the obtained values of the wheel tracking slope WTS_{air} for mixtures compacted at 150°C

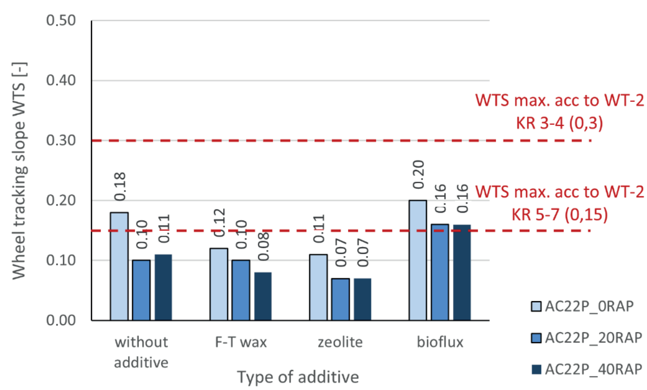

Fig. 10. Summary of the obtained values of the wheel tracking slope WTS_{air} for mixtures compacted at 110°C

5.3. WATER RESISTANCE TEST RESULTS

In order to verify that the requirements for water resistance were met, mixtures with individual additives were tested according to the procedure set out in Annex 1 of the 2014 WT-2 requirements. Fig. 11–12 show the ITSR values obtained for mixtures compacted at 150°C and 110°C, respectively. The figures indicate the minimum acceptable value of the ITSR parameter for the mixtures for the base layer according to the requirements of the WT-2.

The ITSR values obtained, shown in Fig. 11 and 12, indicate that all of the mixtures analyzed met the water resistance requirement of the WT-2 document by achieving at least an index value of 70%.

Comparing the results for mixtures compacted at 150°C and 110°C, it can be concluded that mixtures compacted at a lower temperature have slightly lower ITSR values. This may be due to the slightly more inhomogeneous and less compacted structure of the mixtures compacted at lower temperatures, resulting in a deterioration of their indirect tensile strength.

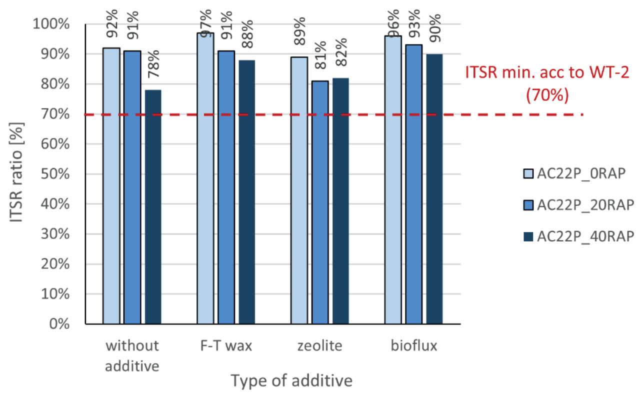

Fig. 11. Summary of the ITSR values obtained for mixtures compacted at 150°C

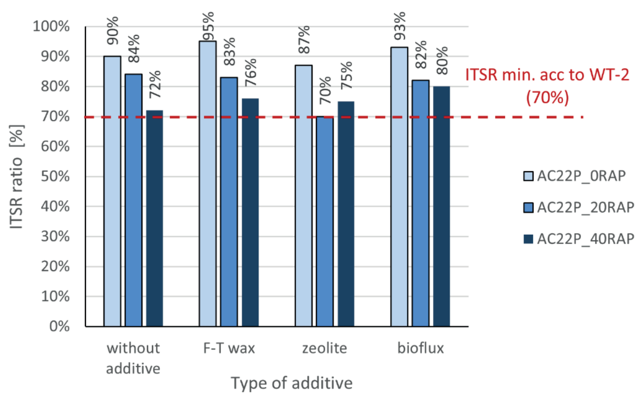

Fig. 12. Summary of the ITSR values obtained for mixtures compacted at 110°C

When analyzing the summarized results, it can also be seen that, in almost all the cases analyzed, the value of the ITSR index decreased with increasing RAP content in the mixture. Only in the case of mixtures with zeolite, the value of the ITSR index for a mixture with 40% of RAP was slightly higher than the value of this index obtained for a mixture with 20% of RAP.

6. CONCLUSIONS

Based on the research and analysis carried out, the following conclusions were drawn:

- Recycling asphalt pavements with the highest possible content of RAP materials in new mixtures plays an important role technologically and economically and is important from the point of view of environmental protection and sustainable development.
- The workability of asphalt mixtures is a parameter which significantly determines their compactability and functional properties.
- Additives used in the WMA technology such as the F-T paraffins, zeolites and plant-derived plasticizers improve the workability of asphalt mixtures, including those with the RAP added.
- Of the additives analyzed, zeolite was the most effective in improving the workability and compactability of asphalt mixtures with RAP, bioflux was the second most effective, the F-T paraffin the least effective.
- The additives analyzed have different effects on the workability of asphalt mixtures with a different RAP content, but the effect of the bioflux additive was the least dependent on the change in an RAP content, which may indicate that it has a greater effect on aged RAP binders than the other additives analyzed, which mainly affect virgin binders.
- The tests carried out confirmed on a laboratory scale the possibility of using up to 40% m/m of cold-dosed RAP when using additives to improve the workability of the mixtures; it would be advisable to verify the possibility of increasing the cold-dosed RAP on an "in-situ" industrial scale.

- With the use of all the additives analyzed, it is possible to reduce the compaction temperature of the asphalt concrete mixtures for the base layer, with the zeolite and bioflux additives having the most effective effect in this respect.
- Mixtures with an increased content of the cold-dosed RAP of up to 40% meet the requirements for a base layer for the KR3-4 traffic load category in terms of resistance to permanent deformation and water resistance, and with the use of selected additives (especially zeolites) also for the KR5-7 traffic load category.

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