

Basic Performance of Fibre Reinforced Asphalt Concrete with Reclaimed Asphalt Pavement Produced in Low Temperatures with Foamed Bitumen

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Abstract. During the reconstruction of road pavements, the reclaimed asphalt pavement (RAP), which is obtained through milling of the worn out existing asphalt, is commonly used for producing new base courses in cold recycling processes. Two of these techniques are most popular: one using mineral-cement-emulsion mixes and one utilizing mineral cement mixes with foamed bitumen. Additionally, some amounts of RAP can be incorporated into traditional hot mix asphalt. The demand for energy efficient and environmentally friendly solutions however, results in a need for development of new techniques that would result in cheaper and more reliable solutions with smaller carbon footprint. The reduction of processing temperatures with simultaneous incorporation of reclaimed material is the most efficient way of obtaining these objectives, but it often results in the overall decrease of bituminous mix quality. The paper presents the possibility of using RAP for producing asphalt concrete in warm mix asphalt (WMA) production process by the use of foamed bitumen modified with Fischer-Tropsch synthetic wax and polymer-basalt fibers. Additionally, a series of reference mixtures were produced to investigate the effects of the additives and of the warm process. The carried out analyses and tests shown that the experimental warm mix asphalt produced with RAP and foamed bitumen returned satisfactory performance. The introduction of synthetic F-T wax in the warm foam bitumen mixes resulted in a significantly improved compaction levels and moisture and frost resistance and the addition of polymer-basalt fibers has further improved the permanent deformation resistance of the mixes. All of the designed and tested mixes have fulfilled the requirements for binding course asphalt concrete with medium traffic loads.

1. Introduction

Today's construction industry pays as much attention to developing and implementing new technologies as to the reuse and recycling of waste materials. Recycling can help to protect the natural environment, reduce the exploitation of natural resources and avoid the degradation of virgin materials used in road pavement construction [1, 2, 3]. Modern road building is implementing innovative and cost effective solutions based on environmentally friendly state-of-the-art technologies (e.g., warm and cold mix production) that provide healthy workplace for its workers and cleaner air for all of us [2-8].



The idea of reducing energy use and limiting emissions in road construction industry has been a subject of interest for many years now by many researchers [9-11]. The reuse of the waste materials (RAP, waste granulate, rubber waste) is undoubtedly advantageous, however this practice less common in Poland compared with other European countries. The precursors of material waste reuse include the Netherlands, Germany, France, Belgium and Denmark. The Netherlands was also one of the first countries in Europe to start waste reuse projects as early as in the 70s due to economic crisis. The earliest cases of using reclaimed asphalt pavement material (RAP) for producing new paving mixes trace back to 1913 [12], but the technology did not become standard practice. In 1970 the members of the Organization of Arab Petroleum Exporting Countries (OAPEC) proclaimed an oil embargo with effects on global economy leading to search for new technologies, including recycling and reduction of the binder use. Cost and environmental benefits are the driving forces in the recycling technologies. These include limiting the use of non-renewable sources of aggregate and asphalt and reducing the cost of asphalt mix production, as aggregates and asphalt are the most expensive components of the mix. In Poland, RAP is currently used in the production of mineral cement mixes with emulsified and foamed asphalt, intended for road base courses [3, 13, 14].

Two main trends predominate in the road material recycling technology. The new mix should have the same properties as the one it was made of or the new mix should have better parameters. This issue has been undertaken to understand the principles of this technology. Compared with other European countries, in Poland the use of RAP is very modest.

2. Materials

The following materials were used to design binding course asphalt concrete AC 22 mixes for roads under medium traffic loads ($0.5 - 7.3 \times 10^6$ ESAL_{100kN}):

- aggregate – obtained from local quarries,
- reclaimed asphalt granulate – derived from the milling local road pavements,
- modifier – Fischer-Tropsch (F-T) wax,
- foamed bitumen,
- polymer-basalt fibers.

2.1. Aggregate

As for the aggregates, a purely limestone mineral mix was used with aggregate dimensions of 0/2 mm, 2/8 mm, 8/16 mm, 16/22 mm and a filler as it can be seen in detail in Table 1.

Table 1. Sieve analysis of the mineral mix

Name of material	Sieve analysis												
	<0.063	0.063	0.125	0.25	0.5	1.0	2.0	4.0	5.6	8.0	11.2	16.0	22.4
limestone filler	100%	91%	91%	7.7%	1.3%								
limestone 0/2	0.9%	2.3%	4.6%	9.8%	21.6%	39.6%	20.9%	0.3%					
limestone 2/8	0.2%					0.6%	15.4%	25.2%	44.8%	13.8%			
limestone 8/16	0.1%	0.2%							2.8%	37.1%	51.6%	8.2%	
limestone 16/22	0.1%	0.2%									3.8%	76.0%	19.8%

2.2. Reclaimed asphalt pavement

To allow the design of the recycled mix, the composition of the asphalt granulate used was determined. Asphalt content of 6.0% was found by the extraction method and the results of granulometric analysis are summarized in Table 2.

Table 2. Sieve analysis of the RAP

Name of material	Sieve analysis												
	<0.063	0.063	0.125	0.25	0.5	1.0	2.0	4.0	5.6	8.0	11.2	16.0	22.4
RAP	11.1%	2.8%	5.0%	7.0%	7.5%	13.2%	18.7%	12.1%	8.5%	7.6%	6.0%	0.5%	

2.3. Fischer Tropsch wax

The Fischer-Tropsch (F-T) synthetic wax is an asphalt modifier with a melting temperature of about 95°C, which dissolves easily in asphalt. Compared with natural paraffin wax, F-T wax has longer hydrocarbon chains. The wax lowers the viscosity of asphalt at processing and after crystallization it develops a crystalline grid thus improving the resistance of the mix to permanent deformation [15].

The synthetic wax was used to produce the asphalt concrete mix at lower temperatures. It was added in the amount of 2.5% by mass relative to the asphalt. The results of the F-T modified foamed bitumen are compiled in Fig. 1.

2.4. Foamed bitumen

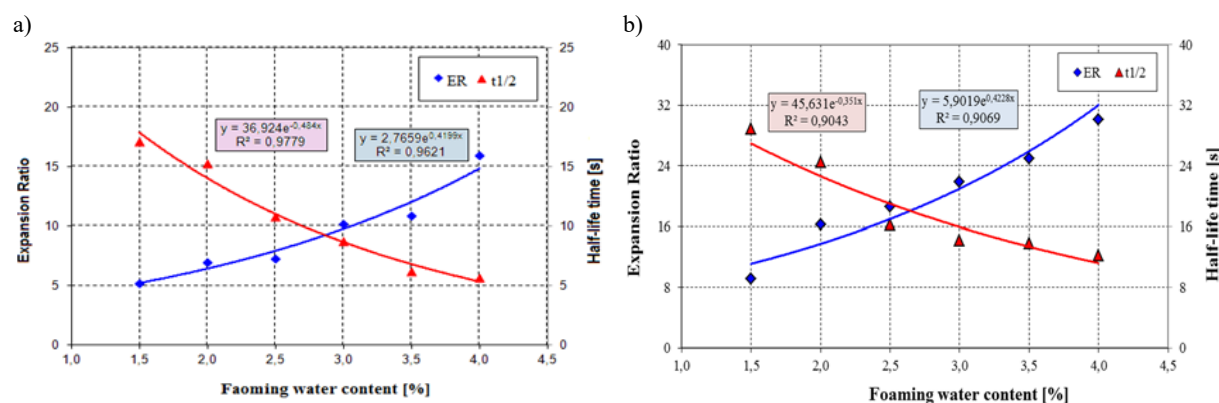
A variety of road bitumen types are used to produce asphalt mixtures. Their basic function is to permanently coat and bind aggregate grains in the mixture. The aggregate with the bitumen should form a monolithic composite with adequate mechanical properties stable throughout the life cycle of the pavement. This depends on the chemical composition and rheological characteristics of the bitumen [16-17].

The mix was produced with foamed bitumen based on road paving bitumen. The parameters of the bitumen 35/50 and 2.5% F-T wax modified bitumen are summarized in Table 3.

Table 3. Basic parameters of bitumen

Property	Unit	Test method	35/50	35/50+ 2.5% F-T wax
Penetration at 25°C	0.1mm	PN-EN 1426	44	32
Softening point	°C	PN-EN 1427	53.9	74.7
Breaking point	°C	PN-EN 12593	-9	-7

After defining basic properties of the bitumen, two characteristic parameters [18] of the foamed bitumen were determined (figure 1): expansion ratio (ER) and half-life time (HL).

**Figure 1.** Foaming characteristics of binders:

a) bitumen 35/50 (ER = 10.17, HL = 8.75s, FWC = 3.0%),

b) bitumen 35/50 + 3.0 % F-T wax (ER = 17.12, HL = 16.25s, FWC = 3.0%)

The test results of the foamed bitumen indicate that at optimum foaming water content (FWC) designated in accordance to [19], the F-T wax modified bitumen has higher expansion ratio and half-life time, which is beneficial.

2.5. Polymer-basalt fibers

Mineral fibers derived mainly from basalt stone, are produced in various lengths and diameters. The fibers show high tensile strength and hardness, resistance to corrosion in acidic and alkaline environment. Basalt fibres adhere to bitumen very well, thus improving the resistance of bituminous mixes to the action of water and frost. Like cellulose fibers, they absorb bitumen and are used as stabilizers in asphalt. Their reinforcing capacity is fibre-size dependent.

An addition of 0.5% polymer-basalt fibres was used in both mixes. The properties of the fibers are compiled in Table 4 and the fibers are shown in Figure 2.

Table 4. Properties of polymer-basalt fibers [20]

Property	
Nominal density	2650 kg/m ³
Humidity	do 1%
Elementary fibers diameter	16 μ
Fiber bundle diameter	0.7-1.0 mm
Fiber length	24 mm
Tensile strength	1680 N/mm ²
Elastic modulus	9.0 kN/mm ²
Elongation	do 3.3%
Melting temperature	1100°C to 1460°C
Operating temperature	-260°C to +750°C



Figure 2. Polymer-basalt fibres (24 mm length)

3. Asphalt concrete mix design

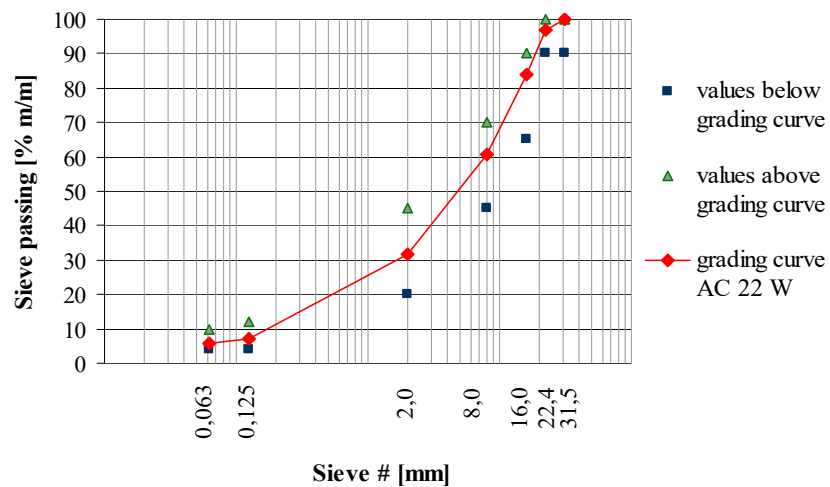
The AC 22 mineral mix for the binding course under the KR4 traffic category was produced in compliance with the grading limits set out in Polish Technical Guideline – 2 : Bituminous pavements for National Highways (TG-2) [21]. Table 5 and Figure 3 summarize the composition of the five following bituminous mixes that were produced for the study:

- Mix A – reference hot mix asphalt concrete with 35/50 bitumen;
- Mix B – reference hot mix asphalt concrete with polymer basalt fiber addition of 0.5% with 35/50 bitumen;
- Mix C – warm mix asphalt concrete with foamed 35/50 bitumen;
- Mix D – warm mix asphalt concrete with foamed 35/50 bitumen modified with 2.5% F-T synthetic wax;
- Mix E – warm mix asphalt concrete with foamed 35/50 bitumen modified with 2.5% F-T synthetic wax, with addition of polymer-basalt fibers in the amount of 0.5%.

Table 5. Composition of the asphalt concrete

Components	% by mass in:	
	mineral mix	AC mix
16/22	15.0	14.46
8/16	20.0	19.28
2/8	20.0	19.28
0/2	26.0	25.06
RAP	15.0	14.46
Lime filler	4.0	3.86
Bitumen 35/50	-	3.6 + 0.9*
SUM	100	100

* Bitumen content in RAP

**Figure 3.** Grain distribution in mineral mix used in AC 22

4. Analysis of test results

Laboratory tests performed to evaluate the described bituminous mixtures included determining their physical and mechanical characteristics:

- air void content (V_m) acc. to EN 12697-8 (Fig. 4a),
- resistance to the action of water (ITSR) acc. to EN 12697-12 (Fig. 4b),
- resistance to permanent deformation (WTS_{AIR} (Fig. 4c), PRD_{AIR} (Fig. 4d)) acc. to EN 12697-22.

In addition to the data shown in Figure 4a-d the Table 6 presents the descriptive statistics for assessing the results. More in-depth statistical analysis is provided in Table 7, where the results of *one-way analysis of variance (ANOVA)* for the type of mix are shown.

Table 6. Descriptive statistics of the obtained results

Mix parameter	Type of the mix	Descriptive Statistics					
		Valid N	Mean	Minimum	Maximum	Std.Dev.	Coef.Var.
V_m (%)	Mix A	6	4.21667	3.9	4.4	0.194079	4.602665
	Mix B	6	4.73333	4.6	4.9	0.136626	2.886465
	Mix C	6	6.33333	6.2	6.5	0.103280	1.630730
	Mix D	6	4.88333	4.7	5.0	0.116905	2.393949
	Mix E	6	4.70000	4.6	4.8	0.089443	1.903037
WTS_{AIR} (mm/10 ³ cycles)	Mix A	4	0.27800	0.276	0.279	0.001414	0.508710
	Mix B	4	0.50500	0.490	0.518	0.011944	2.365211
	Mix C	4	0.53775	0.536	0.542	0.002872	0.534129
	Mix D	4	0.20950	0.208	0.211	0.001732	0.826755
	Mix E	4	0.11375	0.109	0.120	0.005188	4.560991
PRD_{AIR} (%)	Mix A	4	10.14500	10.120	10.160	0.017321	0.170730
	Mix B	4	15.07500	14.970	15.140	0.078528	0.520916
	Mix C	4	14.61750	14.580	14.670	0.037749	0.258246
	Mix D	4	7.05750	7.020	7.080	0.026300	0.372647
	Mix E	4	5.63000	5.600	5.700	0.047610	0.845640

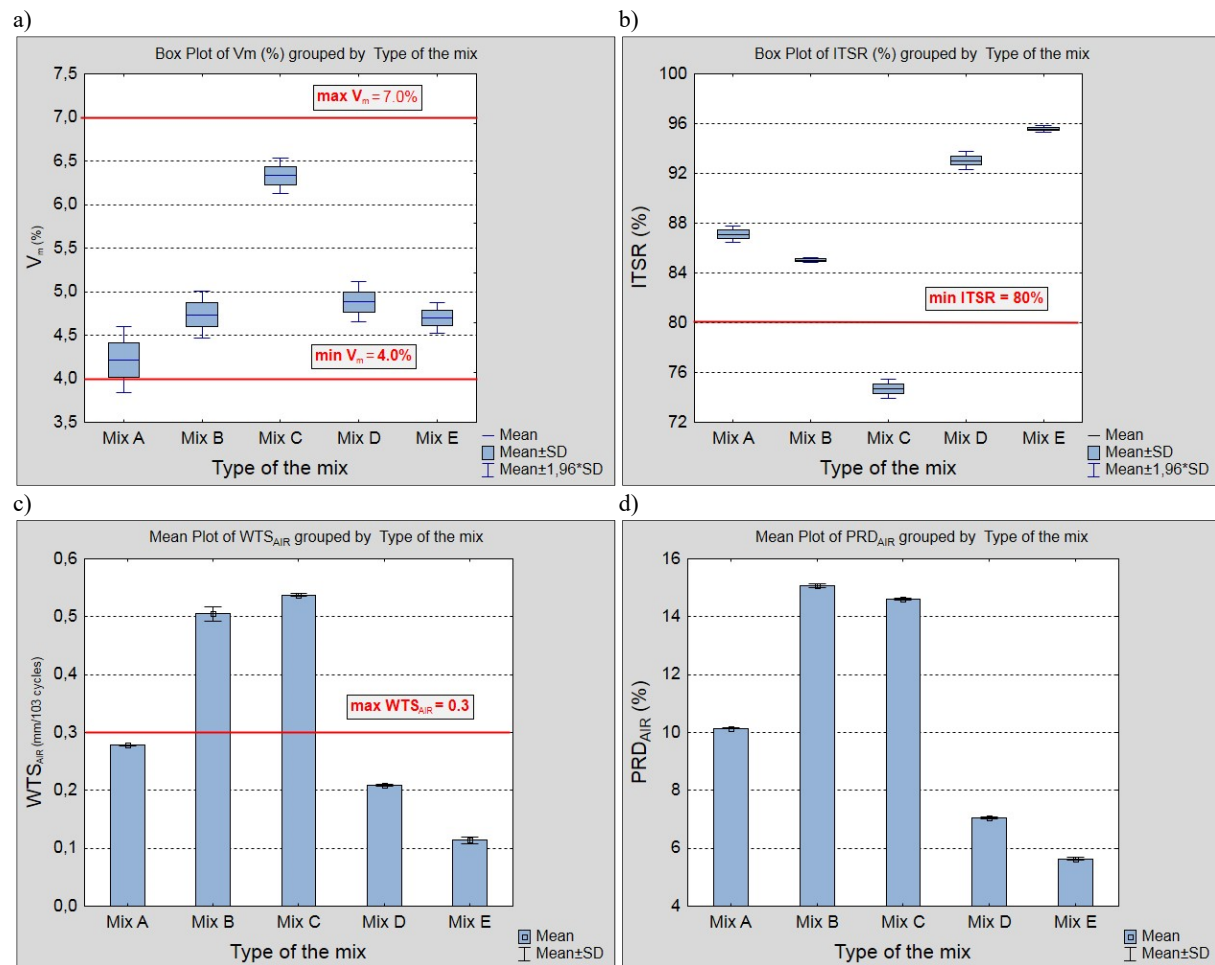


Figure 4. The performance of the tested AC mixes: air void content V_m (a), water resistance ITSR (b), WTS_{AIR} (c) and PRD_{AIR} (d)

Table 7. ANOVA table for the type of the mix factor

Variable	Effect	Univariate Tests of Significance				
		Sigma-restricted parameterization				
		Effective hypothesis decomposition				
		SS	Degr. of Freedom	MS	F	p
V _m (%)	Intercept	742.0213	1	742.0213	41843.31	< 0.001
	Type of the mix	15.3753	4	3.8438	216.76	< 0.001
	Error	0.4433	25	0.0177		
ITSR (%)	Intercept	227540.0	1	227540.0	2668570	< 0.001
	Type of the mix	1593.7	4	398.4	4673	< 0.001
	Error	2.1	25	0.1		
WTS _{AIR} (mm/10 ₃ cycles)	Intercept	2.162189	1	2.162189	59130.05	< 0.001
	Type of the mix	0.551065	4	0.137766	3767.53	< 0.001
	Error	0.000548	15	0.000037		
PRD _{AIR} (%)	Intercept	2207.101	1	2207.101	1017097	< 0.001
	Type of the mix	294.312	4	73.578	33907	< 0.001
	Error	0.033	15	0.002		

Analysis of the results shown in Fig. 4a indicates that all the AC mixes meet the requirements laid down in the TG-2 [21] in terms of air void content, which requires 4.0% to 7.0% for these mixes. The highest amount of air void content was obtained in Mix C produced with foamed bitumen, whereas the highest compaction was possible in reference HMA Mix A. The remaining mixes containing the polymer-basalt fibers as well as the F-T wax modifier obtained intermediate levels of air void content of 4.5% to 5.0%. Based on the result it can be stated that the addition of F-T wax had a beneficial effect on the compaction of the mixes.

Based on the analysis of the ITSR indices of the analyzed mixes it can be stated, that four out of five AC mixes under test met the requirements set out in TG-2 [21] for binding courses for roads under medium traffic category, as the ITSR values were greater 80. It has to be noted that the highest value of the parameter was recorded for the WMA mix with polymer-basalt fibers (Mix E). The lowest ITSR=74.6% was obtained by the Mix C, which was produced using ordinary foamed bitumen in WMA technology, and which also had the highest air void contents.

Analysis of these results indicates that all mixtures investigated satisfied the requirements with regard to V_m and ITSR. It is worth noting that one freezing cycle is used to determine ITSR in Poland, similarly as in Finland. At the same time other CEN (European Committee for Standardisation) member countries, even with similar climate to that in Poland (Slovakia, Germany) do not incorporate the freezing cycle in calculations if this [22]. It has been stated many times that adverse climates require increased number of freeze-thaw cycles in bitumen mix testing to properly evaluate the effects of moisture and frost on the road surface durability [23, 24].

Analysis of the resistance to permanent deformation shown in Fig. 4c and 4d allows stating that in HMA mix the introduction of polymer-basalt fibers resulted in a substantial increase of the WTS_{AIR} and PRD_{AIR} characteristics, thus the mix failed to meet the requirements set out in the TG-2 [21]. Similar increase in WTS_{AIR} was also recorded for the WMA mix with foamed bitumen. In the WMA technology with foamed bitumen and with and without the fibres, the AC mix obtained positive results.

The analysis of the significance was carried out for the influence of the type of mix on the results in all of the measured characteristics in mixes differing in production technique, presence of polymer-basalt fibers and synthetic F-T wax. The analysis showed that all of the described differences in the results were statistically significant with p-values substantially lower than the adopted significance level ($\alpha=0.05$).

5. Conclusion

The review of the literature and the analysis of the test results for the AC 22W mix allow formulating the following conclusions:

- ✓ It is possible to design a bituminous mix with asphalt granulate, which meets the requirements for mixes intended for binding courses.
- ✓ Both HMA and WMA technologies can be utilised to produce the bituminous mix with asphalt aggregate.
- ✓ Compared with the HMA technology, the WMA technology satisfies the requirements in terms of energy saving and environmental effects.
- ✓ The WMA mix with an addition of granulate, synthetic wax and fibres had the best service-related properties in terms of resistance to rutting.
- ✓ Four AC mixes produced in the HMA and WMA technology with asphalt granulate obtained the required characteristics.

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