



## APPLICATION OF THE FOAMED BITUMEN AND BITUMEN EMULSION TO THE ROAD BASE MIXES IN THE DEEP COLD RECYCLING TECHNOLOGY

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**Abstract.** This paper presents findings of a study concerning the influence of binder type on the mechanical properties of road base in the cold recycling technology. The principal aim of this investigation was to evaluate the mixes in scope of susceptibility to moisture and low-temperatures. In the comparative research foamed bitumen and bitumen emulsion were used in four different concentrations (2.0%, 2.5%, 3.0%, 3.5%). The materials used in the study were reclaimed from an existing road construction layers: reclaimed aggregate from the road base and reclaimed asphalt pavement obtained by milling the surface and binder course. Portland cement in 2.0% concentration was used as a hydraulic binder. The evaluated parameters were: indirect tensile strengths, tensile strength retained and indirect tensile stiffness modulus at 25 °C. These tests were complemented by an evaluation of susceptibility to moisture and frost according to modified procedures implemented by American researchers: Tunnicliff, Root and Lottman. Moreover, tests for low-temperature cracking were conducted according to Finnish standard. The investigations showed that the use of foamed bitumen for road base layer produced in the cold recycling technology results in better mechanical properties and resistance to moisture and frost compared to using bitumen emulsion. The use of 2.5% of foamed bitumen and 2.0% of Portland cement in the recycled road base allowed to meet the established criteria.

**Keywords:** bitumen emulsion, deep cold recycling, foamed bitumen, low-temperature cracking performance, moisture and frost susceptibility, Portland cement, road base.

### 1. Introduction

The constantly increasing traffic and axle loads result in introduction of increasingly stringent requirements for pavements, which enforce technical advancements in road construction and modernization techniques. What is more, emphasis is put on efforts ensuring the economic efficiency and environmental friendliness of those new solutions.

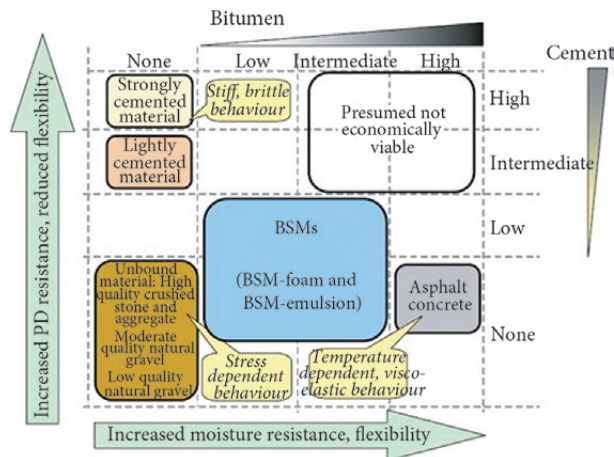
New road construction and rebuilding of existing road network consume large amounts of natural aggregates. Nowadays the worldwide paving industry is facing a shortage of suitable aggregates in general and the high cost of virgin aggregates used in the pavement layers. Therefore, utilization of reclaimed asphalt pavement (RAP) in construction of adequate granular base course layer is an excellent alternative especially in cases where there is a lack of suitable aggregates (Noureldin, Abdelrah 2013). One of the methods utilized for re-use of old pavements in Poland is the deep cold recycling technology, in which the existing construction layers are transformed into road base mineral-cement-emulsion mix. This technology has been used in Poland since the 1990s and its development and usage were

mostly influenced by the difficulties in acquiring new road building materials and increasing waste utilization costs. However, the bituminous emulsion as binder is losing its share in recycling technology across the world on behalf of foamed bitumen. The bitumen foaming technology has been introduced for the first time by Prof Ladis Csanyi and further developed by Mobil Oil in 1960 (Vaitkus *et al.* 2009). Foamed bitumen is produced by injecting small amounts of water and air under pressure into hot bitumen (He, Wong 2008). The deep cold recycling technology with foamed bitumen utilizes a broad spectrum of materials, which range from low quality natural aggregates and recycled pavements to high quality broken aggregates, depending on the desired grade of the produced mix (Mallick, Hendrix 2004). This method is profitable in scope of economic and environmental goals as it reduces the needs for mineral materials and decreases the energy consumption of renovation works, which is decrease of road maintenance costs.

According to *Technical Guideline TG2: Bitumen Stabilised Materials (A Guideline for the Design and Construction of Bitumen Emulsion and Foamed Bitumen*

Stabilised Materials) and Wirtgen Cold Recycling Technology it is advised to select the amount of bituminous (foamed bitumen or bituminous emulsion) and hydraulic binder in deep cold recycling technology with the use of Fig. 1.

The scheme (Fig. 1) shows that the increase in the amount of both agents contributes to the ineffective material use, which is due to the cost of foamed bitumen and



**Fig. 1.** Effect of bitumen binder and cement content on the behaviour of materials according to *Technical Guideline TG2* by Asphalt Academy

**Table 1.** Parameters of foamed bitumen (85N)

Parameters	Unit	Results
Penetration at 25 °C ( <i>EN 1426:2007</i> )	0.1 mm	81
Softening point ( <i>EN 1427:2007</i> )	°C	48.2
Breaking point temperature	°C	-13
Foaming water content	%	2.0
Expansion Ratio	-	15.1
Half-life time	s	14.4
Foam index	s	185.3

**Table 2.** Parameters of bitumen emulsion (C60B5R) and the residual binder

Parameters	Unit	Results
Properties of the Bitumen Emulsion		
Binder content ( <i>EN 1428:2012</i> )	% m/m	59.7
Breaking value ( <i>EN 13075-1:2009</i> )	-	154
Properties of the Residual Binder		
Penetration at 25 °C ( <i>EN 1426:2007</i> )	0.1 mm	85
Softening point ( <i>EN 1427:2007</i> )	°C	44.6

Note: *EN 1426:2007 Bitumen and Bituminous Binders. Determination of Needle Penetration* (valid till 2015-08-31);

*EN 1427:2007 Bitumen and Bituminous Binders. Determination of the Softening Point. Ring and Ball Method* (valid till 2015-08-31);

*EN 1428:2012 Bitumen and Bituminous Binders. Determination of Water Content in Bituminous Emulsions. Azeotropic Distillation Method*;

*EN 13075-1:2009 Bitumen and Bituminous Binders – Determination of Breaking Behaviour. Part 1: Determination of Breaking Value of Cationic Bituminous Emulsions, Mineral Filler Method.*

binder mix constituents. An unbound base has no binder or bitumen present. Higher bitumen content results in greater flexibility of mixes but lower resistance to permanent deformation (Jenkins *et al.* 2007).

Compared to bituminous emulsion, the use of foamed bitumen binder in the road structure results in its higher durability under the conditions of ongoing increase of traffic loads and adverse climate. In addition, this technology reduces the curing time of road base after its completion, which impacts directly the rate of the whole construction process. The application of this technology may be an answer to the problem of mineral resource deficiency in many parts of Poland and it may bring an improvement in technical condition of road surfaces.

Compared to other countries, where this technology is widely used, the magnitude of moisture and low-temperature effects in Poland is amplified due to harsh climate conditions. With this in view, accurate evaluation of resistance to moisture and low-temperature performance is needed in broader scope than stated in conventional requirements for this technology. This issue is mainly related to materials containing reclaimed asphalt pavement, which because of the diversity of the existing types of road structures (in terms of materials and layer thicknesses) is highly heterogeneous.

## 2. Materials and specimen preparation

### 2.1. Bitumen binder tests

The aim of this study was to perform a comparative analysis of two types of deep cold recycled road base mixes (containing different types of bitumen binding agents) designed for KR4 traffic load ( $2.5 \cdot 10^6 < ESAL_{100kN} \leq 7.3 \cdot 10^6$  during 20 year design life, in accordance with the Polish standards).

The reclaimed asphalt pavement used in the study contained 5.1% of bitumen binder (determined in accordance to the *EN 12697-1:2012 Bituminous Mixtures. Test Methods for Hot Mix Asphalt. Soluble Binder Content*). The reclaimed binder was tested for softening point (56 °C according to *EN 1427:2007 Bitumen and Bituminous Binders. Determination of the Softening Point. Ring and Ball Method* (valid till 2015-08-31)) and penetration (43×0.1 mm according to *EN 1426:2007 Bitumen and Bituminous Binders. Determination of Needle Penetration* (valid till 2015-08-31)).

The first type of investigated mixture (Foam-Mix) contained foamed 85N bitumen binder (pre-modified, designed particularly for foaming purposes), which was characterized by superior foaming parameters presented in Table 1: large Expansion Ratio and long bitumen foam Half-Life time (Iwański, Chomicz-Kowalska 2012, 2013). The foamed bitumen was produced by using Wirtgen WLB 10S laboratory equipment, recommended by Kim *et al.* (2009).

The second mixture (Emulsion-Mix) utilized an emulsified bituminous binder, type C60B5R cationic slow setting emulsion based on a 70/100 penetration grade bitumen in accordance with the *EN 13808:2013 Bitumen and Bituminous Binders. Framework for Specifying Cationic Bituminous Emulsions* and its Polish National Annex, which properties are listed in Table 2. These documents specify

that mineral-cement-emulsion mixes for road base in pavements under KR3-KR6 ( $2.5 \cdot 10^6 < ESAL_{100kN} \leq 52 \cdot 10^6$ ) traffic loads should be produced using cationic emulsions with 70/100 penetration bitumen, whereas for KR1-KR2 ( $0.03 \cdot 10^6 < ESAL_{100kN} \leq 0.5 \cdot 10^6$ ) roads use of cationic emulsions with 100/150 penetration bitumen is allowed.

Different concentrations of the binders were investigated to evaluate the influence of the bitumen binder type on the parameters of the mixture. The binding agents were added in amounts ranging from 2.0% to 3.5% in 0.5% increments in relation to mass of mineral mixture. In the Emulsion-Mix the amount of bitumen relates to the residual 60% bitumen content in the emulsion after it has broken, not the emulsion as a whole).

### 2.2. Mix design procedure

The study was performed on recycled road base mixes with two types of binders: foamed bitumen (FB) and bitumen emulsion (BE). The addition of virgin aggregates is recommended to ensure optimum binder content after adding new binders to the mix containing RAP. RAP is considered a cost effective pavement construction material, which is placed in pavement at increasing percentages, however the amount of added reclaimed material is limited by the stiffness of RAP binders (Colbert, You 2012) and homogeneity of the reclaimed material impacting the quality of the resulting mix (Vislavičius, Sivilevičius 2013). This aim was attained by adding reclaimed stone pavement material and virgin aggregates to the mix, which also enhanced the grading. The mixes incorporated materials from two different existing road construction layers: reclaimed asphalt pavement (RAP, 0/25 mm gradation) acquired by wearing and binder course milling, and reclaimed stone pavement (RSP, 0/32 mm aggregate gradation) from an unbound crushed stone base course. All designed road base mixes (Fig. 2) had similar mineral composition and consisted of 48% RAP, 22% RSP and 30% virgin 0/4 mm graded dolomite aggregate. The dolomite aggregate was chosen for a number of reasons: it is extracted in local quarries and readily available, it has supreme quality and high strength and it is widely used for producing bituminous mixtures intended for use in all structural courses of road pavements. The gradation of the materials used in the tests was determined using the wet method according to EN 933-1:2012 Tests for

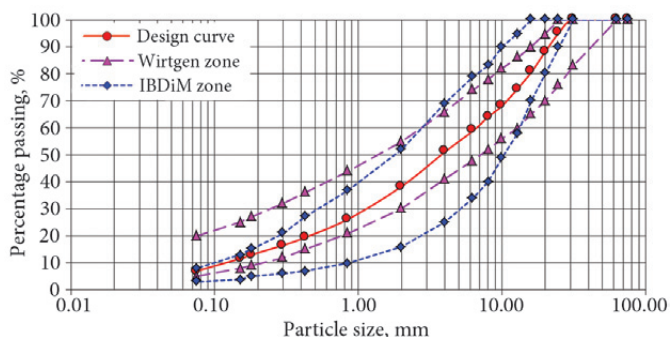
### Geometrical Properties of Aggregates. Part 1: Determination of Particle Size Distribution. Sieving Method.

Considering Polish requirements for mineral-cement-emulsion mixtures (Zawadzki *et al.* 1999) the cement content should range from 1.5% to 4.0%. However, according to *Technical Guidelines TG2* the cement content in Bitumen Stabilised Materials (BSMs) should be less than the bitumen content. The Portland cement content was determined based on previous research (Iwański, Chomicz-Kowalska 2012) and the experiences from test stretches that utilized foamed bitumen technology. Finally, in both studied cases (i.e. Foam-Mix and Emulsion-Mix) the Portland cement class CEM I 32.5 content was set at 2.0%. This amount resulted in optimum mechanical parameters and provided the needed resistance to moisture and frost of the evaluated material. Also, Bissada (1987) recommends the use of 1–2% of the Portland cement to the foamed bitumen mixtures to reduce moisture sensitivity.

The asphalt content in the RAP material was determined using the solvent extraction test according to EN 12274-2:2003 *Slurry Surfacing. Test Methods. Determination of Residual Binder Content* and amounted to 5.4%. The mineral mixture satisfied grading criteria set both for mineral recycled mixes with foamed bitumen and for those with a bitumen emulsion, according to the requirements by Zawadzki *et al.* (1999) and *Wirtgen Cold Recycling Technology*. The water, which satisfied the requirements of EN 1008:2002 *Mixing Water for Concrete. Specification for Sampling, Testing and Assessing the Suitability of Water, Including Water Recovered from Processes in the Concrete Industry, as Mixing Water for Concrete* was used as mixing water in the recycled mineral mixes. During the mix production process conducted according to *Wirtgen Cold Recycling Technology*, the amount of water added ensured 75% OMC (Optimum Moisture Content).

### 2.3. Specimen compaction and conditioning

Current requirements (Zawadzki *et al.* 1999), which were developed and are applied in Poland, for the design phase and quality control of MCE mixtures for road base permit two methods of laboratory specimen compaction: static in a hydraulic press and using Marshall compactor. Authors used the Marshall compaction method with 75 blows per sample face for this study. The curing time of 28 days in ambient temperature is required for dynamically compacted



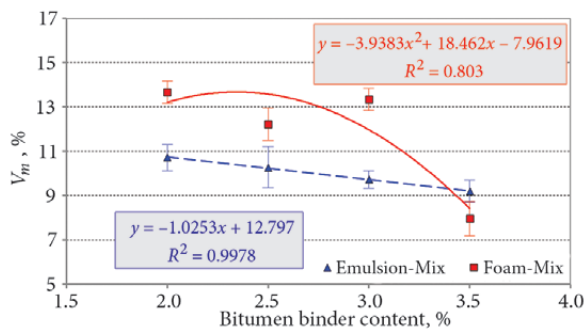
Sieve, mm	Gradation of mineral mix	Sieve, mm	Gradation of mineral mix
63	100	4	38.3
45	95.3	2	26.2
31.5	88.2	1	19.4
22.4	80.6	0.50	16.6
16	74.4	0.25	13.0
11.2	68.1	0.125	11.6
8	64.0	0.063	7.0
5.6	59.0		

Fig. 2. Gradation of the mineral mix for recycled road base with foamed bitumen and with bitumen emulsion

samples. The aggregate was kept in the oven at 25 °C for at least two hours before being mixed with foamed bitumen, because temperature has been reported to be an important factor affecting the mechanical properties of foamed bitumen mixes (Van De Ven *et al.* 2007).

For the Foam-Mix, foreign-developed experiences and procedures were adopted due to the lack of Polish guidelines for recycled mixes with foamed bitumen. The Foam-Mix specimens were also compacted using a Marshall compactor with 75 blows per face. There is a number of different curing practices for mixes with foamed bitumen. The Authors applied an accelerated curing method proposed by Ruckel *et al.* (1982) recommended by the *Technical Guideline TG2*, which is equivalent to a conventional 28 day curing mentioned before (Jenkins 2000). According to this approach, the specimens after compaction are stored in moulds for 24 hours in +20 °C. After that, the moulds are removed and samples are cured unsealed for the next 72 hours in thermal chamber with air circulation at +40 °C.

The physical and strength parameters of all samples (Emulsion-Mix and Foam-Mix) were tested within the first 24 hours after the end of curing (after reaching room temperature).



Type of binder	Foamed bitumen				Bitumen emulsion			
Binder content, %	2.0	2.5	3.0	3.5	2.0	2.5	3.0	3.5
Mean (%)	13.76	12.36	13.47	8.18	10.72	10.28	9.72	9.20
St. dev. (%)	0.49	0.73	0.50	0.77	0.59	0.93	0.39	0.50

Fig. 3. The impact of the bitumen binder content on air void content (the error bars represent the standard deviation)

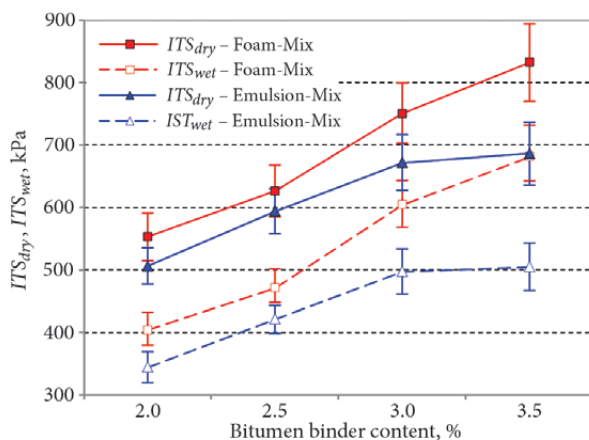


Fig. 4. The impact of the binding agents (FB, BE) content on indirect tensile strengths before and after soaking

### 3. Experimental program

The aim of the research was to assess the influence of bitumen binder (FB, BE) and its amount (2.0%, 2.5%, 3.0% and 3.5%) in the composition of recycled road base mixtures on the physical and mechanical properties of the samples and their resistance to moisture and frost susceptibility. Homogeneity of the conducted research work was an important element of the study. It should be noted that the mean value of the results in each specimen variant (FB, BE and different levels of binder amounts) had a variation coefficient less than 15%.

To evaluate physical and mechanical parameters of the road base mixes resistance to moisture and low-temperature in terms of the type and the amount of the bitumen binder added, the following features were analysed:

- air void content ( $V_m$ ) according to guidelines by Zawadzki *et al.* (1999);
- indirect tensile strength before and after soaking in water ( $ITS_{dry}$ ,  $ITS_{wet}$ ) and tensile strength retained ( $TSR$ ) according to the *Technical Guideline TG2 and Wirtgen Cold Recycling Technology*;
- stiffness modulus ( $ITSM$ ) at 25 °C (indirect tensile configuration, IT-CY) in accordance with the European Standard *EN 12697-26:2012 Bituminous Mixtures. Test Methods for Hot Mix Asphalt. Stiffness*;
- low-temperature cracking resistance based on the indirect tensile strength after curing at -2 °C ( $ITS_{low-temp.}$ ) in compliance with *Finnish PANK 4302 Standard Asphalt Pavements. Low Temperature Resistance. Method of Determining Indirect Tensile Strength*;
- tensile strength retained after soaking in water ( $TSR_{water}$ ) according to Root-Tunnicliff procedure *ASTM D4867 Standard Test Method for Effect of Moisture on Asphalt Paving Mixtures* and after freeze-thaw cycles ( $TSR_{freeze-thaw}$ ) according to the American guidelines, i.e. modified Lottman test formulated in *AASHTO T283 Standard Method of Test for Resistance of Compacted Bituminous Mixture to Moisture Induced Damage* standard and applied to Polish conditions (number of freeze-thaw cycles increased from 1 to 18).

### 4. Results and discussion

The results of the laboratory tests of the air void content ( $V_m$ ) with the emphasis on values of the dispersion around the averages are presented in Fig. 3. Figure 4 shows indirect tensile strengths of the soaked and unsoaked specimens versus different bitumen binders (FB, BE) across the dosing range. Similarly, the Fig. 5 presents the results of tensile strength retained ( $TSR$ ) derived from those samples.

The analysis of results presented in the Figs 3 to 8 leads to a conclusion that both the type and amount of bituminous binder had significant effect on the properties of recycled road base mixes. What is more, not all of the mixtures met the technical requirements by Zawadzki *et al.* (1999) and *Wirtgen Cold Recycling Technology*. The mean

value of air void content in all Emulsion-Mix samples ranged from 9.20% to 10.72% giving satisfactory results (the required air void content of specimens prepared in Marshall hammer compactor is 9.0–16.0%). The samples with foamed bitumen yielded more diverse results, where the highest amount of binder (3.5%) resulted in air void content well below 9% required in Poland (Zawadzki *et al.* 1999) and 10% according to German guidelines by *Wirtgen Cold Recycling Technology*. Additionally, such high values in the range of 12.36–13.76% could be explained by the difficulties in coating of fine particles at lower (2.0–3.0%) bitumen binder contents. Mixes with emulsion have better workability and compactibility due to major water content in the emulsion (40%) compared to foamed bitumen (2.0%). This resulted in the decrease of air void content along with the increase of emulsion content.

The results shown in Figs 4 and 5 show clearly that the amount of bituminous binder in the Emulsion-Mix and Foam-Mix has a significant effect on the resistance to moisture. The increase in indirect tensile strength was associated with the rise of bitumen binder (FB, BE) content in the specimens regardless of the used binder. However, the dry samples with FB better than those with BE. Also, after the water-curing process the Foam-Mix specimens gave better results. In the Emulsion-Mix samples the increase of binder content from 3.0% to 3.5% did not influence significantly the  $ITS_{dry}$  and  $ITS_{wet}$  parameters. All of the tested samples satisfied the requirements ( $ITS_{dry} \geq 225$  kPa,  $ITS_{wet} \geq 100$  kPa) according to the guidelines *Technical Guideline TG2* and *Wirtgen Cold Recycling Technology*. The results of TSR show that the road base with bituminous binder content in the range from 2.0% to 3.5% produced in recycling technology with FB is more resistant to moisture damage compared to BE mix. Although, the increase of bitumen binder content in both cases resulted in an increase in the TSR parameter values. The criterion of moisture damage resistance was met for the mixtures with FB in full spectrum of bitumen binder contents. On the other hand, the use of BE in the smallest investigated concentration (2.0%) resulted in unsatisfactory TSR results that were less than 70% (*Asphalt Academy 2002*). This procedure allows the evaluation of susceptibility to moisture damage of bitumen-stabilized materials. Based on the TSR parameter it is possible to designate optimum bituminous binder content in the mix.

One of the methods to evaluate the stiffness of bitumen bound materials is to measure the indirect tensile stiffness modulus (ITSM) using the further described IT-CY method. The stiffness modulus expresses the relationship between stress and strain in given temperature and loading time. In addition, the visco-elastic characteristics are contained in the expression of stiffness modulus (Yan *et al.* 2010). The measurements were taken on a samples under cyclic vertical axial loading with controlled straining (horizontal deformation: 5  $\mu$ m). The test parameters were: temperature: 25 °C, rise time: 124 $\pm$ 4 ms and Poisson's ratio: 0.35. The relationships between average

ITSM value and bitumen binder content in the tested mixtures are shown in Fig. 6.

The data presented in Fig. 6 show that the amount of bituminous binder had varied effect on the stiffness modulus depending on the binder type. The recommendations in the *Wirtgen Cold Recycling Manual* of 2004 suggest that the stiffness modulus for recycled mixes with FB and composed of 50:50 RAP/crushed stone blend should be contained between 2500 MPa and 4000 MPa. The mix with 3.5% FB content did not meet this criterion reaching the indirect tensile stiffness modulus value of over 4000 MPa. It should be noted that the change of bitumen binder content effects the stiffness modulus very differently depending on the type of binder. Increase in the concentration of FB results in an increase of ITSM, whereas, with the increase of BE content the stiffness modulus decreases. This is probably caused by the differences in the structure of produced mixes. BE, which is in fluid form and contains large quantities of water, easily coats fine and coarse aggregate particles. FB containing only 2.0% of water, on the other hand, binds mainly to the fine particles creating a form of dispersed reinforcement.

In order to determine the resistance of the road base to Polish climatic conditions the test spectrum was widened to include research procedures for moisture and

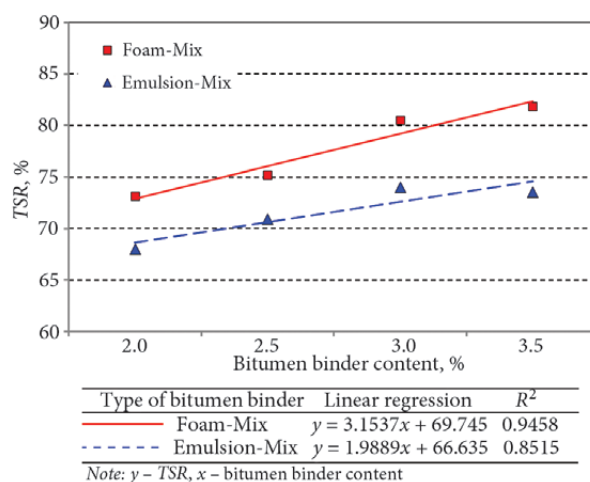


Fig. 5. Influence of the bitumen binder (foam, emulsion) content on tensile strength retained

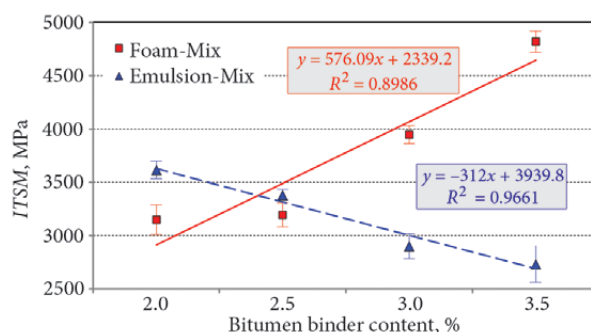


Fig. 6. The impact of the type and amount of bitumen binder on indirect tensile stiffness modulus

low-temperature susceptibility assessment of traditional bitumen mixes in the hot technology. The evaluation was conducted according to modified procedures applied by Tunnicliff, Root (*ASTM D4867*) and Lottman (*AASHTO T283*) after laboratory simulation of moisture and frost influence (18 freeze-thaw cycles) and after curing at  $-2\text{ }^{\circ}\text{C}$  according to PANK 4302 standard.

The results of moisture and low-temperature resistance of the recycled mixes with BE and with FB are presented in Figs 7 and 8. Figure 7 depicts indirect tensile strengths ( $ITS_{low-temp.}$ ) at  $-2\text{ }^{\circ}\text{C}$ . Table 3 and Fig. 8 present the impact of the type and amount of binder on the

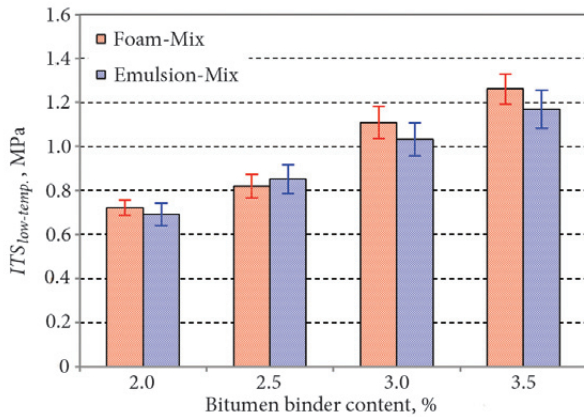


Fig. 7. Indirect tensile strengths ( $ITS_{low-temp.}$ ) of road base mixes after curing at  $-2\text{ }^{\circ}\text{C}$  according to PANK 4302

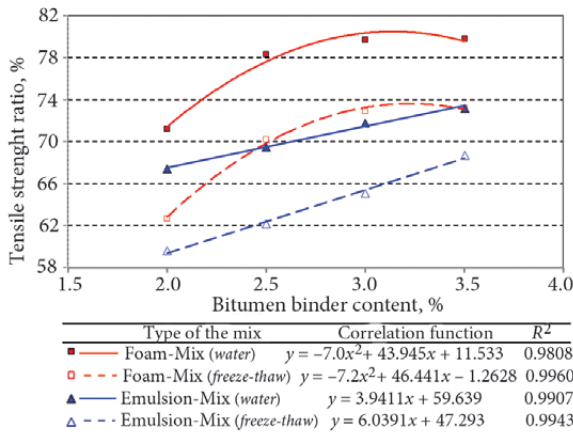


Fig. 8. Relationship between the type and amount of binder in the road base mixes and tensile strength ratios after curing in water ( $TSR_{water}$ ) and after thaw-freeze cycles ( $TSR_{freeze-thaw}$ )

retained strengths after moisture ( $TSR_{water}$ ) and frost ( $TSR_{freeze-thaw}$ ) conditioning.

As mentioned, low-temperature cracking resistance tests were conducted under the Finnish standard. In relation to asphalt concrete layers, it is assumed that the pavement is protected against low-temperature cracking when its  $ITS$  measured at  $-2\text{ }^{\circ}\text{C}$  is less than 4.8 MPa. All the recycled road base mixes yielded values less than 4.8 MPa, thus satisfying the assumed criterion. Mean strength values were at comparable levels considering the given amounts of binder. The least resistance value of 0.69 MPa, was recorded for Emulsion-Mix with the least amount (2.0%) of binder.

Evaluation of moisture and frost resistance of the mineral-cement-emulsion samples in accordance with modified American specifications was a relevant element of this study. Susceptibility to moisture and to the combined effects of moisture and frost (thaw-frost cycles) is expressed as a ratio of  $ITS$  of samples conditioned in moisture and frost and samples conditioned in room temperature. When the decrease in  $ITS$  induced by the damaging effects of moisture and frost is less than 30% (the ratio is  $>70\%$ ) (Jaskuła, Judycki 2008) the conventional mixes (e.g. asphalt concrete) are assumed to be resistant to those effects.

When analysing the recycled mineral mixes performance in terms of moisture resistance, then the use of FB appears to be more beneficial compared to BE. All road base mixes with FB appeared to be moisture-resistant, while some mixes with emulsion showed poor performance in this area (the  $TSR_{water}$  coefficients were more than the minimum recommended value only for mixes containing 3.0% and 3.5% of the binder). The road base with the BE exhibited insufficient resistance to the combined action of water and frost, regardless of the amount of the emulsion used. The highest result for the Emulsion-Mix of 68.7% was achieved only for the maximum binder content. In contrast, water and frost resistance of Foam-Mix was ensured by 2.5% FB content in the recycled road base mix ( $TSR_{water} = 78.3\%$ ,  $TSR_{freeze-thaw} = 70.2\%$ ). The resistance to climatic factors increased along with the increasing amount of FB in the road base. Accordingly, the mineral mixes with FB were more resistant both to water and to the combined action of water and frost.

### 5. Statistical analysis

The two-way Analysis of Variance (ANOVA) was used to assess the effects of factors in the experiment domain:

Table 3. Mean indirect tensile strengths of Foam-Mix and Emulsion-Mix samples depending on the bitumen binder content

Feature	Type of the mix	Foam-Mix				Emulsion-Mix			
	Bitumen binder content, %	2.0	2.5	3.0	3.5	2.0	2.5	3.0	3.5
Indirect tensile strengths, MPa	Dry samples ( $ITS_{dry}$ )	0.553	0.627	0.751	0.833	0.506	0.594	0.672	0.686
	Water-cured samples ( $ITS_{water}$ )	0.394	0.491	0.599	0.664	0.341	0.413	0.483	0.502
	After thaw-freeze cycles ( $ITS_{freeze-thaw}$ )	0.347	0.440	0.547	0.609	0.302	0.370	0.438	0.472
Tensile strength ratio, %	Water action ( $TSR_{water}$ )	71.2	78.3	79.7	79.8	67.4	69.5	71.8	73.2
	Water and frost action ( $TSR_{freeze-thaw}$ )	62.7	70.2	72.9	73.2	59.6	62.2	65.1	68.7

bitumen binder type (Foam-Mix, Emulsion-Mix) and its content (2.0%, 2.5%, 3.0% 3.5%) on the distribution of the analysed parameters of the recycled road base mixes. The Duncan multiple range test was used to investigate which groups of results significantly differed from the others. Each feature was analysed for the mixes differing in the type and amount of the binder in nine replicates. The total of 72 data items were collected for purposes of the analysis.

First, mean values of the features in groups were compared, i.e. the statistically significant effect of the main factor and the variation in the recycled mixes type and amount of bitumen binder was analysed. When it was found that both factors had a significant impact on the tested features, then the Duncan multiple comparison method was used to check the equality of means for each pair of factor-based groups (type, amount). Table 4 presents the analysis of variance of the features in terms of the recycled material type the and the amount of FB used in the road base mixes.

In accordance with the adopted hypothesis that assumed a lack of impact of the factors in question, the results from the tests were subjected to a multiple factor analysis. The *p*-value for *F*-statistic was less than 0.0001, i.e. considerably below the assumed significance level of  $\alpha = 0.05$ . Accordingly, the null hypothesis was rejected with a 5% error. This means that there were at least two groups in which the mean values of the considered

characteristics differed significantly. Then, each of the factors (type and amount) was analysed for their significance. It is important to note that empirical significance levels for both factors (type, amount) were considerably below the assumed significance level ( $\alpha = 0.05$ ). The *p*-value helped to find the major significant effect of the binder type and amount factor.

It can then be concluded that the type and amount of both components (FB, BE) in the recycled mixes had a significant impact on the distribution of the means of the investigated features.

Having adopted the alternative hypothesis that the means of the characteristics are different, multiple comparison tests were performed to evaluate the contrasts of the obtained mean values. The results of computations of repeated measurements tests conducted under the Duncan method are summarized in Table 5.

Figure 9 shows the visualization of differences that were revealed in the distribution of the selected characteristics in the sub-groups (two or four). The Figs 9a to 9d present the box plots corresponding to the sub-groups.

The statistical analysis demonstrated that higher mean values for the all tested mechanical parameters were associated with the FB mixes. In addition, the distribution of the characteristics indicates that the type and amount of the binder used in the recycled road base mixes significantly affected the distribution of the analysed parameters.

**Table 4.** Significant influence evaluation (two-way ANOVA) of the factors (type, amount) on tested features

Feature	Symbol	Source*	DF	Sum of squares	Mean of squares	F Ratio	<i>p</i> -value
Air void content	$V_m$	<i>T</i>	1	69.6003470	69.6003347	52.47	<0.0001
		<i>A</i>	3	132.001549	44.0005162	33.17	<0.0001
Indirect Tensile Strength	$ITS_{dry}$	<i>T</i>	1	104160.369	104160.369	39.22	<0.0001
		<i>A</i>	3	571685.306	190561.769	71.76	<0.0001
Moisture resistance	$ITS_{wet}$	<i>T</i>	1	173725.651	173725.651	88.15	<0.0001
		<i>A</i>	3	533867.140	177955.713	90.29	<0.0001
	$TSR$	<i>T</i>	1	0.05951250	0.05951250	1012.66	<0.0001
		<i>A</i>	3	0.06603750	0.02201250	374.56	<0.0001
Indirect tensile stiffness modulus	$ITSM$	<i>T</i>	1	6142342.60	6142342.60	18.57	<0.0001
		<i>A</i>	3	2188102.80	729367.600	1.789	<0.0001
Low-temperature cracking	$ITS_{low-temp.}$	<i>T</i>	1	0.03166806	0.03166806	6.14	0.0157
		<i>A</i>	3	2.82874861	0.94291620	182.83	<0.0001
Water action	$ITS_{water}$	<i>T</i>	1	0.18736381	0.18736381	55.55	<0.0001
		<i>A</i>	3	0.49783877	0.16594626	49.20	<0.0001
	$TSR_{water}$	<i>T</i>	1	826.211250	826.211250	863.41	<0.0001
		<i>A</i>	3	564.063750	188.021250	196.49	<0.0001
Water and frost action (freeze-thaw cycles)	$ITS_{freeze-thaw}$	<i>T</i>	1	0.14834905	0.14834905	102.03	<0.0001
		<i>A</i>	3	0.49461229	0.16487076	113.39	<0.0001
	$TSR_{freeze-thaw}$	<i>T</i>	1	616.005000	616.005000	514.97	<0.0001
		<i>A</i>	3	978.165000	326.055000	272.58	<0.0001

Note: \* *T* - type, *A* - amount.

**Table 5.** Duncan multiple comparison tests for determining the differences between the effects of the factors

Feature	Factor <sup>1)</sup> T	Duncan Grouping <sup>2)</sup>	Mean	Factor <sup>3)</sup> A in %	Duncan Grouping <sup>4)</sup>	Mean
$V_m$	Foam-Mix	A	11.9431	2.0	A	12.2394
				3.0	B&A	11.5944
	Emulsion-Mix	B	9.97670	2.5	B	11.3183
				3.5	C	8.68720
$ITS_{dry}$	Foam-Mix	A	690.830	3.5	A	759.500
				3.0	B	711.520
	Emulsion-Mix	B	614.760	2.5	C	610.340
				2.0	D	529.820
$ITS_{wet}$	Foam-Mix	A	540.170	3.5	A	593.090
				3.0	B	550.900
	Emulsion-Mix	B	441.930	2.5	C	445.890
				2.0	D	374.320
TSR	Foam-Mix	A	0.77500	3.5	A	0.78000
				3.0	B	0.77000
	Emulsion-Mix	B	0.71750	2.5	C	0.73000
				2.0	D	0.70500
ITSM	Foam-Mix	A	3779.41	3.5	A	3778.63
				3.0	B	3425.44
	Emulsion-Mix	B	3159.81	2.0	C	3383.25
				2.5	D	3291.13
$ITS_{low-temp.}$	Foam-Mix	A	0.97778	3.5	A	1.21500
				3.0	B	1.07056
	Emulsion-Mix	B	0.93583	2.5	C	0.83556
				2.0	D	0.70611
$ITS_{water}$	Foam-Mix	A	0.53685	3.5	A	0.58344
				3.0	B	0.54054
	Emulsion-Mix	B	0.43483	2.5	C	0.45176
				2.0	D	0.36762
$TSR_{water}$	Foam-Mix	A	77.7109	3.5	A	76.5000
				3.0	B	75.7500
	Emulsion-Mix	B	70.7317	2.5	C	73.9000
				2.0	D	69.3000
$ITS_{freeze-thaw}$	Foam-Mix	A	0.48590	3.5	A	0.54052
				3.0	B	0.49248
	Emulsion-Mix	B	0.39512	2.5	C	0.40469
				2.0	D	0.32435
$TSR_{freeze-thaw}$	Foam-Mix	A	70.3357	3.5	A	70.9500
				3.0	B	69.0000
	Emulsion-Mix	B	64.2722	2.5	C	66.2000
				2.0	D	61.1500
$TSR_{water}$	Foam-Mix	A	11.9431	3.5	A	0.78000
				3.0	B	0.77000
	Emulsion-Mix	B	9.97670	2.5	C	0.73000
				2.0	D	0.70500

Note: <sup>1)</sup> T – type of bitumen binder; <sup>2)</sup> Means with the same letter not significantly different; <sup>3)</sup> A – amount of bitumen binder; <sup>4)</sup> Means with the same letter not significantly different.



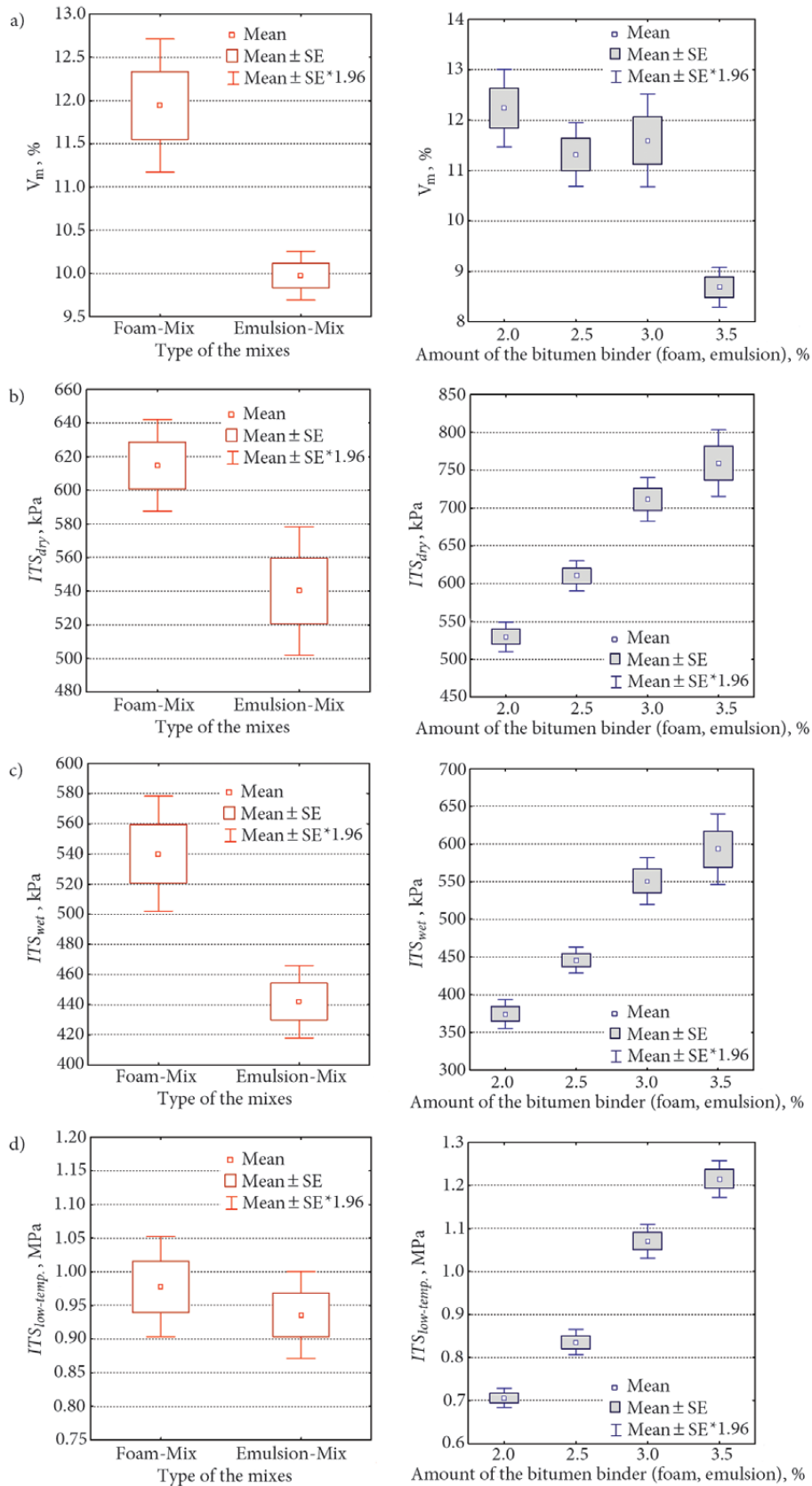


Fig. 9. Distribution of the tested features: a – air void content  $V_m$ , b – dry indirect tensile strength  $ITS_{dry}$ , c – wet indirect tensile strength  $ITS_{wet}$ , d – indirect tensile strength before after curing at  $-2^\circ\text{C}$   $ITS_{low-temp}$

The analysis of the distribution of characteristic  $V_m$  (Fig. 9a) shows that the recycled road base mixes with the least amount of bitumen binder had the highest mean value of the parameter. The least air void content was observed in mixes containing the highest amount of binder. This may be due to the binder filling the void spaces, which caused the underestimation of the true value of the characteristic. The application of the binder in amounts of 2.0–3.0% (Table 5b) did not lead to any statistically significant differences.

The calculations conducted according to the Duncan method (Table 5a) and analysis of the results summarized in Figs 9b–9d demonstrated that the mean value of *ITS* features in the mixes containing FB was significantly higher than the mean value of this characteristic recorded for Emulsion-Mix. In addition, the amount of the binder had a significant effect on the variability in the distribution of the *ITS* characteristic. The obtained means revealed that regardless of the binder type its increasing concentration in the recycled road base mixes was a major factor in determining the *ITS* increase.

The analyses conducted in this study led to the conclusion that the type of binder and its amount in the recycled road base mixes have a significant effect on the mean values of the characteristics that reflect the moisture and low-temperature resistance of the mixes. Those mixes, which contained FB had higher moisture and low-temperature resistance in the binder evaluation range (2.0–3.5%), while the mixes with the BE showed no resistance to frost ( $TSR_{freeze-thaw} = 64.27$ ).

## 6. Conclusions

Based on the comparative analysis of the test results of the recycled road base mixes with foamed bitumen and bitumen emulsion the following conclusions drawn.

1. An increase in the bitumen binder (foamed bitumen and bitumen emulsion) content from 2.0% to 3.5% caused an increase in indirect tensile strength (dry and soaked) of the road base material. Additionally, the application of foamed bitumen resulted in higher dry and wet indirect tensile strengths of the recycled material in comparison to the application of bitumen emulsion, regardless of the binder content.

2. Cold recycled bituminous mixtures for road base with foamed bitumen exhibited higher resistance to the damaging effect of moisture compared to mixtures with mineral-cement-emulsion mixtures.

3. The recycled road base with foamed bitumen yielded higher indirect tensile stiffness modulus than that with bitumen emulsion. The values of the indirect tensile stiffness modulus increased clearly in the mixes with foamed bitumen while the stiffness modulus decreased in the Emulsion-Mix with bitumen emulsion.

4. Bituminous mixtures for road base in cold recycling with foamed bitumen exhibited higher resistance to moisture and low-temperatures in comparison with the bitumen emulsion.

5. The two-way factorial Analysis of Variance and the Duncan multiple comparison tests revealed a significant

effect of the type and amount of binder (foamed bitumen, bitumen emulsion) on the properties of the recycled road bases. Mechanical parameters and moisture and frost susceptibility of foamed bitumen mixes were considerably higher than those of mixes with the bitumen emulsion (Emulsion-Mix)

6. It is necessary to determine the water and frost resistance of bituminous mixtures with foamed bitumen to properly evaluate the durability of road bases produced in moderate climate zones. Another argument for the calculation of the water and frost resistance of those mixes is the high content of air voids present in the recycled material. The tests confirmed that the tensile strength retained criterion used alone is insufficient as a measure of the recycled road base response to the action of water and it should be complemented with the proposed modified AASHTO *T 283 Standard Method of Test for Resistance of Compacted Bituminous Mixture to Moisture Induced Damage*, method.

## Acknowledgements

The scientific research has been conducted as a part of the Project “Innovative recourses and effective methods of safety improvement and durability of buildings and transport infrastructure in the sustainable development” financed by the European Union from the European Fund of Regional Development based on the Operational Program of the Innovative Economy.

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Received 27 January 2014; accepted 4 September 2014