EXPERIMENTAL STUDY OF WATER AND FROST RESISTANCE OF FOAMED BITUMEN MIXES IN THE COLD RECYCLING TECHNOLOGY

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ABSTRACT

According to the climatic conditions in the Central European countries road pavement structure should be moisture and frost resistant. This problem is especially important for pavements rehabilitated in the cold recycling technology. Determining the physical and mechanical properties as well as moisture and frost resistance depending on the binder and filler contents is an essential element before its introduction to road building. The tests were performed on mineral recycled base mixes with foamed bitumen, in which the material from the existing layers was used. The bitumen binder was added to the recycled material in the amount of 2,0% to 3,5%, and hydraulic binder (cement) of 1,0% to 2,5% with changes every 0,5% at variable. Investigated the effect of different binder contents on the dry and soaked indirect tensile strength (ITS), tensile strength retained (TSR) and indirect tensile resilient modulus of a recycled mixes. The measurements of resistance to the effects of water and frost according to the AASHTO T283 method and the resistance to low temperature cracking according to the PANK 4302 methods confirmed that used foamed bitumen in the cold recycling technology is resistant to these climatic factors. The results obtained were subjected to the optimization process, which allowed to state that with the application of 2,5% foamed bitumen and 2,0% of cement the base has the required physical and mechanical properties as well as water and frost resistance according to the applied criteria.

Keywords: cold recycling technology, foamed bitumen, cement, moisture and frost resistance, optimization process

1. INTRODUCTION

Cold in situ recycling using foamed bitumen has gained recognition and popularity around the world as a cost effective technique of rehabilitating road pavement layers. Environmental and economic pressures have caused engineers to reuse the existing pavement materials rather than to import material from quarries. Lewis and Collings [1] observed, that foamed bitumen treated material forms a flexible layer with good fatigue properties that is not prone to shrinkage and is resistant to the ingress of water.

Foaming technology was first introduced by Professor Ladis Csanyi [2] and then further developed by Mobil Oil in the 1960s by creating an expansion chamber. In this laboratory investigation, foamed bitumen was produced by a Wirtgen foaming machine type WLB 10. The Wirtgen foaming equipment has been recommended as a very consistent in terms of releasing the quantity of bitumen as specified in [3].

Currently, the pavement cold recycling technology using mineral-cement-emulsion (MCE) mixes is popular in Poland. However, a constant development in the area of rehabilitation of the road network in the country related to the need to improve the load capacity of surface construction emphasises the necessity to introduce a more advanced cold recycling technology by Polish contractors, in which foamed bitumen is used instead of bitumen emulsion. This bitumen binder enables to obtain more durable road pavements under heavy traffic loads and more unfavourable climatic factors [4].

The cold recycling technology with foamed bitumen is widely used mainly in Africa and Australia, where the impact of temperatures below 0ºC (frost) and water on the road construction is not significant. Consequently, in requirements [5] only tensile strength retained (TSR) was taken as water resistance criterion in case of this kind of pavement. This parameter enables to assess the water tightness and the resistance to the effects of water.

The climatic conditions in Poland are much more unfavourable with regard to both water and frost interaction with the pavement structure than in countries where this technology is used. In moderate climate conditions no detailed data is available for the pavement structure with foamed bitumen regarding its water and frost resistance. Consequently, it was a vital research aspect to assess the resistance of the material to these two factors in a range which is broader than the requirements prepared for this technology.

2. TESTED MATERIAL

2.1 Foamed bitumen tests

In road building there are various kinds of bitumen to use that differ by origin, the kind of petroleum which they are made of, group composition, consistency and mechanical parameters. Consequently, it can be expected that every kind of bitumen subjected to the process of foaming will react in a different way. In road practice, the bitumen of different penetration is used in the foaming technology worldwide and according to this, an important element of the tests was to preliminarily determine the suitability of bitumen applied in Polish conditions [6].

The characteristics of the foam were investigated using the foamed bitumen laboratory model WLB10, which has been used by many researchers and practitioners for the production of foamed bitumen [7, 8]. To produce the foam, the testing method proposed by the TG2 South African guidelines was used [9].

The tests were performed on six kinds of road bitumen. The suitability analysis covered the determination of the standard properties and foaming parameters (Table 1).

Table 1 : Characteristics of bitumens used in the foaming process

Kind of bitumen	Penetration at 25ºC (0,1 mm)	Softening point (ºC)	Fraass breaking point (ºC)	The optimum foaming water content (%)	Expansion ratio (ER)	Half-life time (τ½) (sec)	Foam Index (FI) (sec)
50/70O	55	50.2	-9	2.5	6.0	8.6	3,9
160/220O	196	41.4	-16	2.5	6.7	11.4	47.3
70/100L	82	47.2	-11	2.5	5.9	6.0	38.6
70/100eL	74	49.4	-12	2.5	6.2	6.3	40.1
50/70N	68	52.8	-10	2.0	10.4	9.7	102.5
80N	81	48.2	-13	2.0	15.1	14.4	185.3

Foamed bitumen is characterized by Expansion Ratio (ER), Half-life time (τ½) and Foam Index (FI). The expansion ratio is defined as the maximum volume over its original volume (before foaming) and half-life time is defined as the time it takes (in seconds) for foam to become a half of its maximum volume. It can be seen, that choosing the optimum quantity of foamant water is a trade-off between ER and τ½. The increase of foamant water results in a higher expansion ratio, but shorter half-life time. The foam index can be utilized to determine the optimum foaming water content for specific bitumen. The foam index is a measure of the change in expansion ratio with time, which reflects the combined effect of the viscosity (ER) and stability (τ½) with time. This is a measure of the stored energy in the foam for a specific bitumen foamed at a known temperature with foaming water at a determined application rate. The required foam index for bitumen is dependent on the purpose for which the foam is to be used [10]. The optimum foaming water content was determined by the amount to obtain the maximum expansion ratio and the longest half-life time of foamed bitumen.

The guidance proposed by Wirtgen [5] is that the minimum permissible values of ER and τ½ should be 8 and 6 seconds respectively. In contrast, Muthen [11] suggest minimum values of 10 and 12 seconds and Asphalt Academy [9] 7 and 7 seconds for ER and τ½ respectively. However, according to Jenkins [10] foam index should be > 125 second.

The expansion of the bitumen and the half-life time are dependent mainly on: the type and temperature of base bitumen, the working pressure of bitumen, water and air, the quantity of foamant water added and temperature of the mixing chamber or vessel into which the foamed bitumen is sprayed.

To describe the dependence between the foaming parameters (ER and τ½) of the tested bitumen and its water content the exponential and power function was used. A correlation determined on the basis of the obtained results for these parameters has quite a good determination coefficient (R^2>0.91), which allows to assess the dependence between tested features as acceptable [6]. The 80N bitumen (Fig 1) with 2.0% of foaming water content under air pressure of 500 kPa and water pressure of 600 kPa obtain the best of foaming parameters. Thus, its application for the deep cold recycling should guarantee obtaining base course of high mechanical parameters.

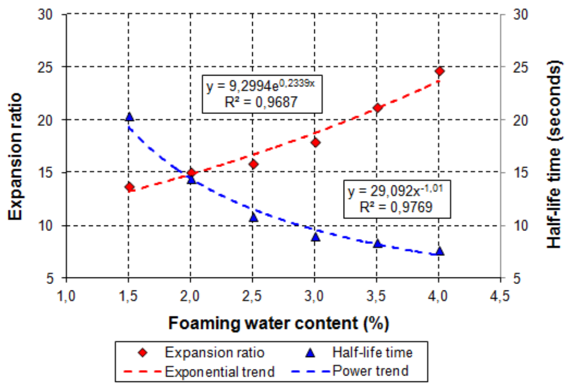


Figure 1 : Foaming characteristics (ER and τ½) of bitumen 80N at foaming temperature 170ºC

2.2 Mix design procedure

The tests were performed on the base course mixes with foamed bitumen, in which the material from the rehabilitation construction layers of road surfaces was used. The mineral mix meeting the grading criteria according to the requirements [9, 12]. The designed mineral mix of the base course (Fig 2) contained 48% of milled asphalt layers (RAP), 22% of the existing stone base and 30% of a new material - 0/4 mm dolomite aggregate.

In order to determine the influence of the amount of bitumen binder (foamed bitumen) and the hydraulic binder (cement) on the physical and mechanical properties, the recycled base course mixes with various contents of these components were designed. In tests, as the bitumen binder 80N bitumen was applied with adding 2.0% of foaming water. Its content in the recycled mix was 2.0%, 2.5%, 3.0%, and 3.5%. In order to determine the influence of cement quantity on the physical and mechanical properties of the recycled base its concentration in mixes amounted to 1.0%, 1.5%, 2.0% and 2.5% in relation to the mineral mix. Cement was applied to obtain the higher value of the tested parameters and to increase the content of the fraction below 0.063 mm in the recycled material. The kind of binder depends on the quality of mineral mix, the organic component content, the content of the fraction below 0.063 mm, the grading and the kind of aggregate. The water was also added to the recycled mixes in order to obtain optimal compaction conditions.

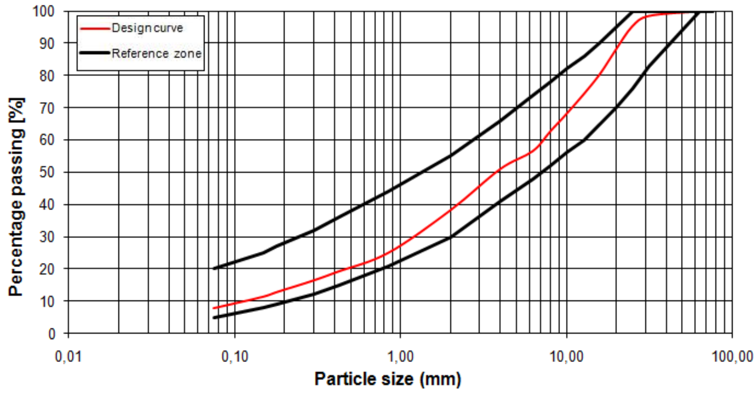


Figure 2 : Grading curve of the mineral mix in the cold recycling technology with foamed bitumen

2.3 Specimen preparation and curing procedure

In Poland two laboratory curing methods are recommended for bitumen emulsion treated materials depending on the compacting method: Marshall (dynamic compaction) and the hydraulic press (static compaction) [13]. All samples were compacted according to Marshall methods (75 blows per face).

There are many curing procedure for the recycled mixes with foamed bitumen. In the tests were used the procedure proposed in 1983 by Ruckel et al. [14] and adopted by Interim Technical Guidelines (TG2) and utilized by many researchers [15, 16]. According to the TG2 [9] for foamed bitumen treatments, the recommended curing time is 24 hours in the form and 72 hours at 40ºC in oven. The aggregate was kept in the oven at 25ºC for at least two hours before mixing with foamed bitumen, because temperature has been reported to be an important factor affecting the mechanical properties of foamed bitumen mixes [17, 18].

An assessment of the uniformity of the conducted tests was an important element of the project. The tests were performed on series of 9 samples. The presented results are the mean values. It should be noted that the average of results for each variant of the amount of bitumen binder and hydraulic binder were characterized by a coefficient of variation which was less than 15%.

3. METHODOLOGY AND TEST RESULTS ANALYSIS

The aim of the research project was to determine the impact of foamed bitumen (FB) and cement (C) content on the physical and mechanical properties of the pavement rehabilitation with the deep cold recycling technology and to determine its water and frost resistance.

In order to determine the physical and mechanical properties of the recycled mixes with regard to the amount of in bitumen binder and hydraulic binder (FB, C) the following parameters were determined: air void content (V_m), indirect tensile strength (ITS_{dry}, ITS_{wet}) and indirect tensile stiffness modulus (ITSM).

Over the years, the Marshall stability test method has been used as a design method for foamed asphalt mixtures. However, Muthen [11] recommended that the optimum foamed bitumen content should be selected based on the relationship between indirect tensile strength and foamed bitumen content. According to the TG2 [9] the indirect tensile strength (ITS_{dry}) values are determined from the 100 mm diameter and 63 mm high specimens after cured time to reach a constant mass. The results obtained after soaking these specimens for 24 hours at 25ºC are termed ITS_{wet}. The ratio of ITS_{wet} and ITS_{dry}, expressed as a percentage, is the Tensile Strength Retained (TSR). This procedure is aimed at evaluating the moisture susceptibility of the bitumen stabilized materials. Using this features we can indicate the optimum binder content and select the active filler type and content [9].

Stiffness of bituminous material can be measured using the indirect tensile stiffness modulus (ITSM) test, which is a non-destructive method and has been widely used for determination of stiffness modulus values. The stiffness modulus expresses the relationship of stress and strain at a certain temperature and load. In addition, the visco-elastic characteristics are contained in the expression of stiffness modulus.

The stiffness modulus tests are carried out in a controlled stress or strain mode by applying five compressive load pulses along the vertical diameter of cylindrical specimen and the resultant displacements on horizontal diameter measured by means of suitable linear transducers (LVDT). This testing method uses cylindrical specimens that may be prepared in the laboratory or sampled from the field. The test method was run in accordance with European standard PN-EN 12697-26:2007 [27]. The standard target parameters pertaining throughout testing are as follows: test temperature: 20ºC, rise time: 124±4ms, horizontal deformation: 5µm and Poisson's ratio: 0,35.

The results of the laboratory tests of the air void content with the emphasis on values of the dispersion around averages were presented in Figure 3. Figure 4 shows the relationship between indirect tensile strength soaked and unsoaked specimens with different foamed bitumen and cement contents. The results of the indirect tensile stiffness modulus tests (ITSM) at 25ºC due to [12] are shown in Figure 5.

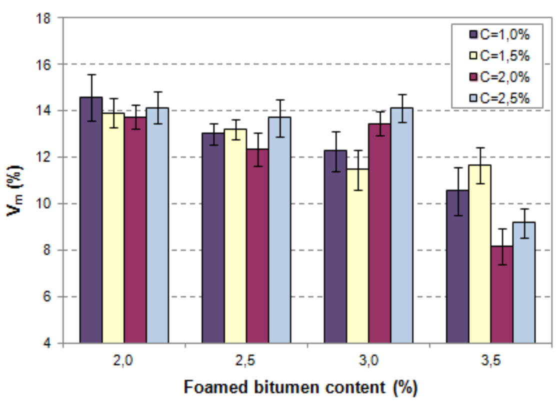


Figure 3 : The impact of the bitumen binder and cement content on air void content

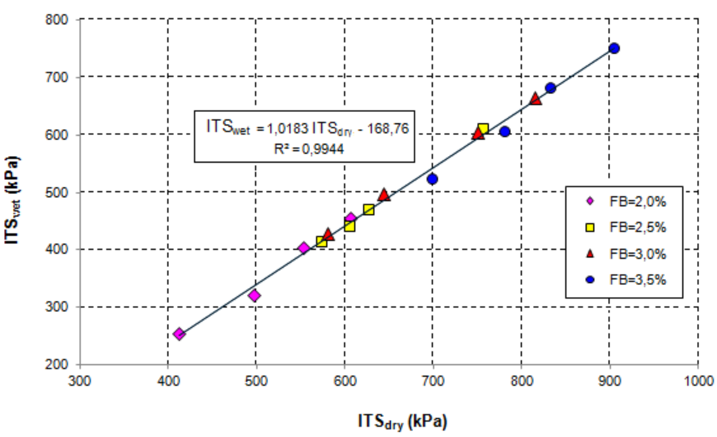
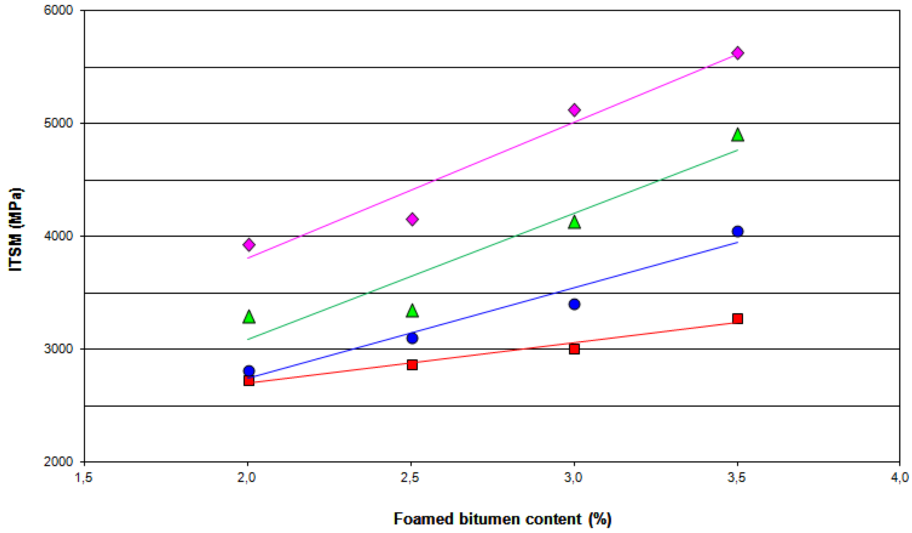


Figure 4 : Relationship between ITS_{dry} of recycled base course mixes and ITS_{wet}



Cement content	Linear Regression	Coefficient of Determination R^2
1.0%	y=259.12x+1878.3	0.9560
1.5%	y=752.00x+947.75	0.9889
2.0%	y=1152.2x+610.93	0.8985
2.5%	y=1239.6x+1265.9	0.9048
Note	y-ITSM, x-foamed bitumen content	

Figure 5 : Effect of the bitumen binder and cement content on indirect tensile stiffness modulus (ITSM)

The analysis of the tests results presented in Figure 3 of the recycled base mixes reveals that the amount of the applied foamed bitumen as well as the amount of cement have an important impact on the tested features.

While assessing the air void content it can be noticed, that the increase of the bitumen binder content causes the decrease of this parameters. The base course mixes with 2.0%÷3.0% bitumen binder obtain the air void content according to Wirtgen requirements (from 10 to 15%) [5] for materials with foamed bitumen and for bitumen emulsion according IBDiM requirements (from 9 to 16%) [13].

The test results proved that an increase in the recycled mixes of concentration binder content (FB, C) led to an increase in indirect tensile strength (soaked and unsoaked). According to the Technical Guideline TG2 [19] all mixes obtain the higher values than the minimal required for this type of mineral material (ITS_{dry}>225 kPa, ITS_{wet}>100 kPa).

The analysis of the tests results presented in Figure 5 proves that the foamed bitumen (FB) and cement (C) contents in the mixes have a significant influence on the changes of the indirect tensile stiffness modulus (ITSM). The values of ITSM increased when the foamed bitumen and cement content increased. The value of the determination coefficient R^2 was above 0,89 for the obtained linear regressions. According to [12] the indirect tensile stiffness modulus (ITSM) of recycled mixes with foamed bitumen should be characterized by the indirect tensile stiffness modulus in the range from 2500 MPa to 4000 MPa. The base course mixes with 2.5%÷3.5% foamed bitumen contents reach higher values than the minimal required for this type of the mineral material (RAP/crushed stone).

In order to establish a correlation between stiffness modulus (ITSM) and strength properties (ITS) tests were conducted at temperature of 20ºC. The ITSM tests were carried out using a standard testing procedure, i.e. Poisson's ratio 0.40 and target rise time 124 ms at 5 microns target horizontal deformation. The relationship between ITSM values of base course mixes and ITS mixes are shown in Figure 6.

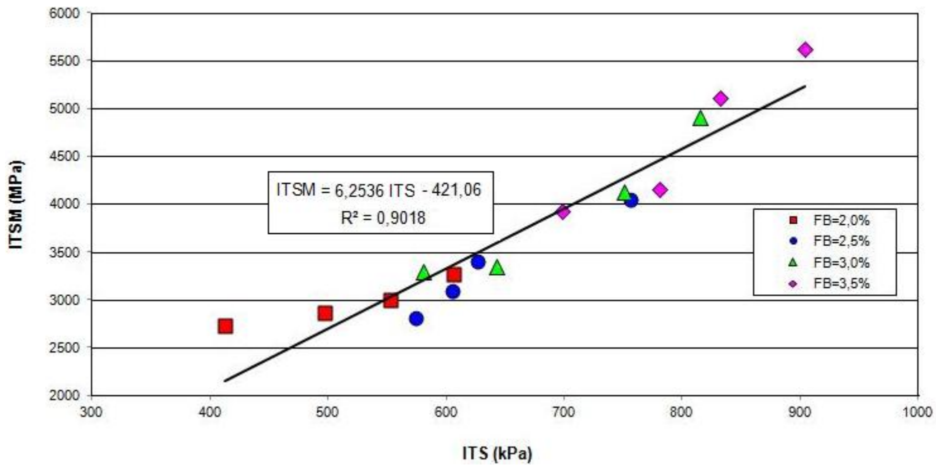


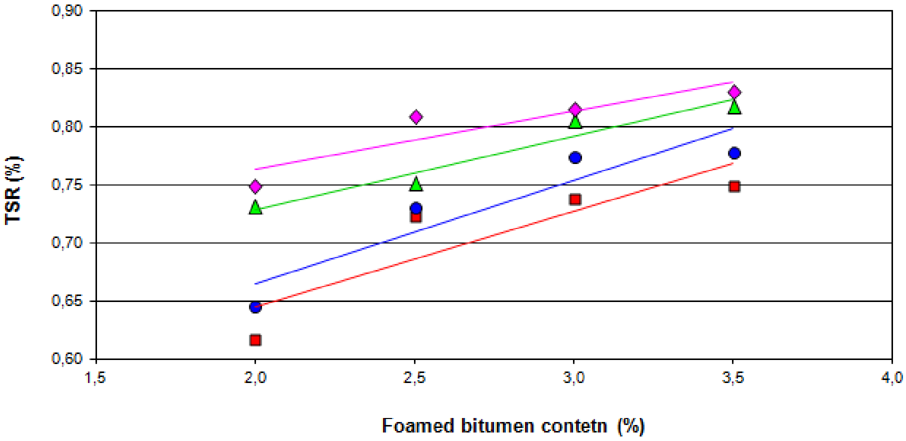
Figure 6 : Correlation between indirect tensile strength (ITS) value and indirect tensile stiffness modulus (ITSM)

Figure 6 gives strong support that ITS and ITSM have approximately linear correlation with R^2 equal 0.9018. It is found that ITSM value is about 6 times of ITS value. This correlation is very important in order to understand a relationship of fundamental and engineering properties of foamed bitumen materials.

In order to determine the resistance of the base course to the climatic conditions in Poland the tests were widened to include research procedures used to assess water and frost resistance of traditional mineral and bitumen mixes in the hot technology. To do this assessment American and Finnish methods were used - PANK 4302 standard enables to assess the mineral and bitumen mixes resistance to low temperature cracking, while modified AASHTO T283 method covers the influence of water on mineral and bitumen mixes as well as water interaction and freezing cycles.

In order to assess water and frost resistance of mineral mixes with foamed bitumen the following parameters were determined: tensile strength retained (TSR) according to the Technical Guideline TG2 [9], resistance to low temperature cracking according to the Finnish PANK 4302 standard [20] and indirect tensile strength after curing in water and frost according to the AASHTO T283 method [21, 22]. Investigation of the resistance to low temperature cracking of the material for surface pavement with foamed bitumen according to PANK 4302 [20] is based on determination of the indirect tensile strength (ITS_{-2^oC}) of specimens kept in an air chamber at the temperature of -2ºC for 16 hours. The tests are conducted in the Marshall apparatus at the temperature of -2ºC.

The test results of resistance to the effects of destructive climatic factors of the recycled base course with foamed bitumen have been presented in Figure 7 and 8. A relation between tensile strength retained (TSR) and the foamed bitumen and cement content has been shown in Figure 7, while Figure 8 presents such relation for indirect tensile strength (ITS_{-2^oC}) at -2ºC according to PANK 4302 (the error bars represent the standard deviation).



Cement content	Linear Regression	Coefficient of Determination R^2
1.0%	y=0.0826x+0.4793	0.7682
1.5%	y=0.0892x+0.4865	0.8560
2.0%	y=0.0631x+0.6028	0.9458
2.5%	y=0.0503x+0.6630	0.8190
Note	y-TSR, x-foamed bitumen content	

Figure 7 : The impact of the binding agents (FB, C) content on tensile strength retained (TSR)

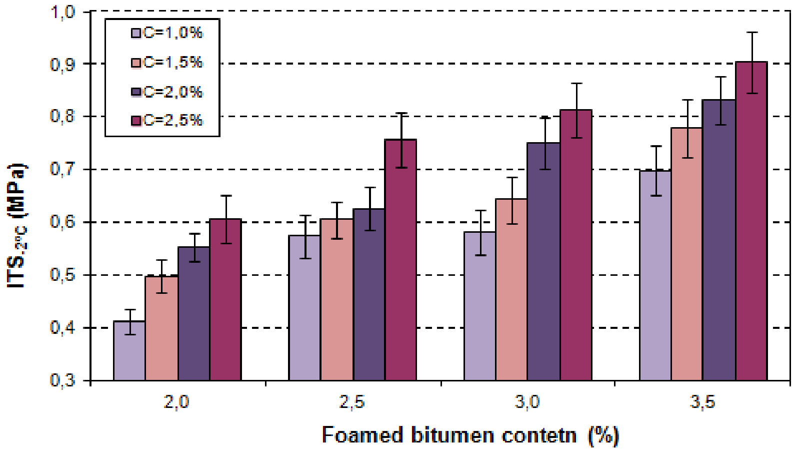


Figure 8 : The impact of the foamed bitumen and cement content on indirect tensile strength (ITS_{-2^oC}) according to PANK 4302

The analysis of test results (Fig 7 and 8) shows, that the bituminous binder (foamed bitumen) and hydraulic binder (cement) content have a meaningful influence on TSR and ITS_{-2^oC} values of foamed bitumen treated materials.

The increase in content of the binding materials in recycled pavement mixes leads to obtaining TSR at the higher level. Using linear regression trend lines were fit to the data. The slope of the TSR-foamed bitumen content curve decreased from 0.0826 to 0.0503 as the cement content increased from 1.0% to 2.5%. This result indicates that recycled mixes with higher amount of cement content increased in strength faster than mixtures with lower cement content. Tightness and water resistance is ensured with 2.0% cement content in recycled pavement which already contains 2.5% of foamed bitumen. In this case TSR was higher than the required minimal value 0.7 [9]. Consequently, it is useless to apply more cement, which can cause cracking in pavement layer and layers of road surface construction above.

Indirect tensile strength at -2ºC according to PANK 4302 [20] after the curing process, which simulated the effects of low temperatures, did not exceed the limiting value of 4.8 MPa. It can be concluded that as a result, such pavement structures will be resistant to low temperature cracking during winter.

A thorough assessment of water and frost resistance of the tested kinds of recycled pavement mixes was performed according to modified AASHTO T283 method [21, 22, 23].

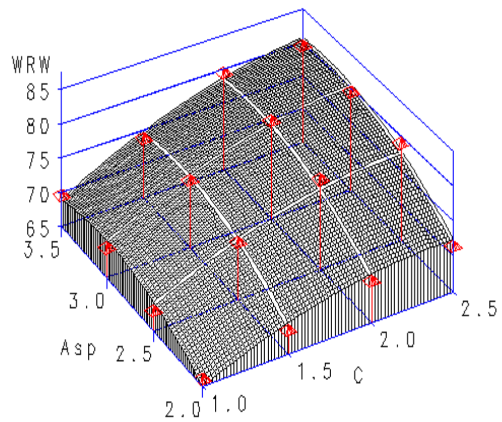
The experiment was realized according to the research program within the confines of two factorial design of experiment type of 2^2. Having analysed the influence of the bitumen and hydraulic binder amount (FB and C) on the water and frost resistance tested according to AASHTO T283 it was concluded, that in order to describe them, it is statistically essential to use the polynomial model of the second order [24, 25]. The regression formula model can be write down as a following equation:

$$y = b_0 + \sum_{i=1}^{n} b_i \cdot x_i + \sum_{i=j=1}^{n} b_{i=j} \cdot x_i \cdot x_j + \sum_{i=1}^{n} b_j \cdot x_j^2$$

Where x_i is the amount of foamed bitumen (%), x_j is the amount of cement (%) and $b_i \div b_j$ are the experimental ratios values.

The visual presentation of results and response surface regression models was presented in Figure 9.

a)



b)

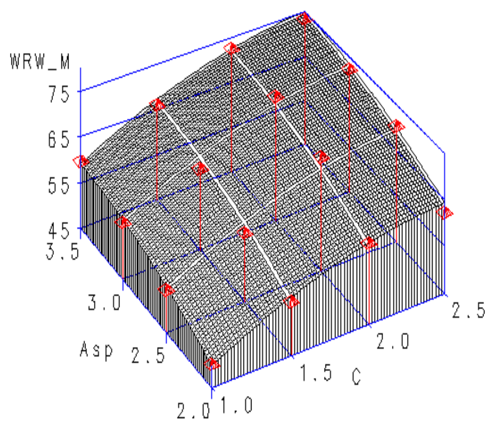


Figure 9 : The impact of foamed bitumen and cement contents on strength ratio of water resistance WR_W (a) and strength ratio of water and frost resistance WR_{W+M} (b)

Analyzing the received results of features such as strength ratio of water resistance (WR_W) and strength of water and frost resistance (WR_{W+M}), at first the assessment of Pearson's correlation coefficient R^2 and significance of influence of the factors (FB-Asp, C) with the aid of variance analysis, were needed.

The evaluation of Pearson's correlation coefficient and significance of influence of factors were presented in Table 2. The obtained results of the experimental coefficients of the regression models have been presented in Table 3.

Table 2 : Pearson's correlation coefficient and evaluation of impact tested factors

Feature	R^2	p-value	
		Foamed bitumen (FB)	Cement (C)
WR_W	0.9618	< 0.0001	< 0.0001
WR_{W+M}	0.9640	< 0.0001	< 0.0001

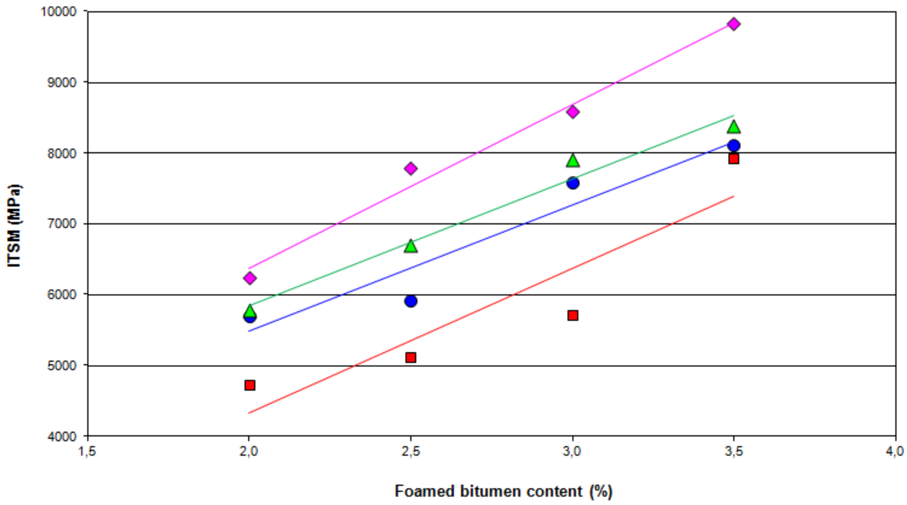
Table 3 : The values of experimental coefficients for the properties: WR_W, WR_{W+M}

Feature	b_o	b_1	b_2	b_3	b_4	b_5
WR_W	10.68050	30.83050	14.51150	1.92400	-5.47500	-3.82500
WR_{W+M}	-13.15250	27.25250	28.30750	0.46000	-3.87500	-5.52500

Analyzing the received regression models for tested parameters (Fig 9) it is proven, that the amount of both binding agents (FB, C) has an important impact on water and frost resistance of the base course material with foamed bitumen. Results, on significance level equal 0.05, revealed the significant influence of the amount and kind of binder (FB, C) on changes of mechanical parameters (p-value < 0.001). Together with the increase of binder and cement concentration the value of the parameters rises.

When the strength ratio is higher than 0.7 [22, 23], it is assumed that the mixes made in traditional technologies are water and frost resistant. Analysing the results of the tested base course mixes for water and frost resistance, it is possible to prove that the required value was not obtained in every case. It should be noted that with 2.5% bitumen binder content and 2.0% cement content the required strength characteristics of tested material were obtained. The strength radio for the tested material was higher than the minimal value (WR_W=78.3%, WR_{W+M}=70.2%), which assures its water and frost resistance. While higher resistance is ensured by the application of higher content of these two binding materials in the recycled base composition.

The assessment of frost resistance of the recycled base course mixes with foamed bitumen was conducted on the basis of the indirect tensile stiffness modulus (ITS) at the temperature of -10ºC (Fig 10). While the analysis of water resistance of mineral mixes with foamed bitumen – the ITSM – was carried out at the temperature of +25ºC on soaked samples (Fig 11).



Cement content	Linear Regression	Coefficient of Determination R^2
1.0%	y=1788.1x+1908.9	0.9171
1.5%	y=2038x+257.79	0.8491
2.0%	y=1796.7x+2250.3	0.9765
2.5%	y=2318.1x+1734	0.9861
Note	y-ITSM, x-foamed bitumen content	

Figure 10 : The impact of the foamed bitumen and cement content on indirect tensile stiffness modulus ITSM at -10ºC

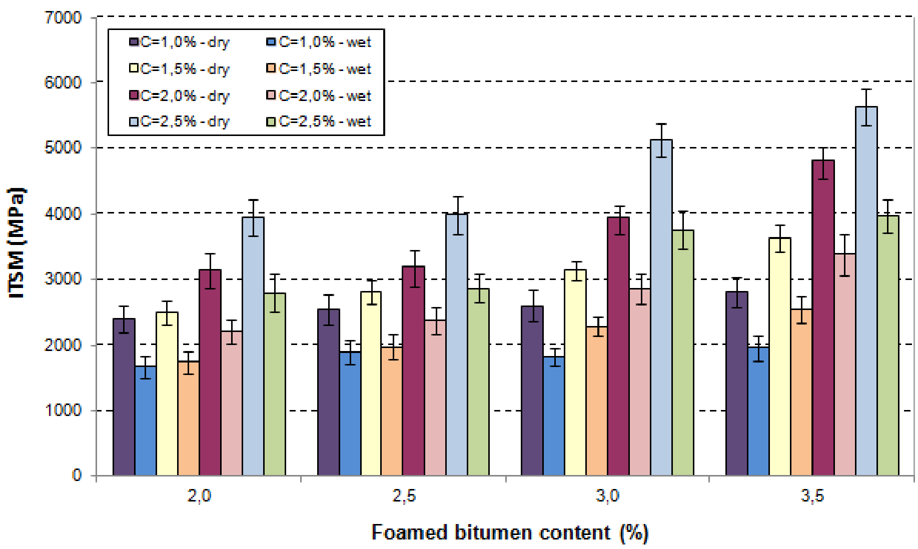


Figure 11 : Effect of the binding agents (FB, C) content on indirect tensile stiffness modulus (ITSM) soaked and unsoaked base course mixes

The analysis of the tests results presented in Figure 10 proves that the foamed bitumen and cement contents have a significant influence on the changes of the indirect tensile stiffness modulus (ITSM) at the temperature of -10ºC. The ITSM values were in the range of 4716MPa÷9824,8MPa. Moreover, a slight increase (by about 5%) of the indirect tensile stiffness modulus at the cement content of 1,5%÷2,0% was recorded. The data are fitted with the linear regression trend lines of the determination coefficient R^2 above 0,84.

The test results presented in Figure 11 indicate that mineral mixes with foamed bitumen after soaking with water have lower ITSM values by about 30%. Lancester et al. [26] recommend the minimal indirect tensile stiffness modulus for dry samples at the level of ITSM=6000 MPa while for soaked samples ITSM=1500 MPa. Taking this criterion into account, all the investigated samples had the required water resistance (ITSM > 1500 MPa).

The analysis in Figure 12 of the impact of temperature changes on mean indirect tensile stiffness modulus of mineral mixes with foamed bitumen was performed in the temperature range of -10ºC to +40ºC.

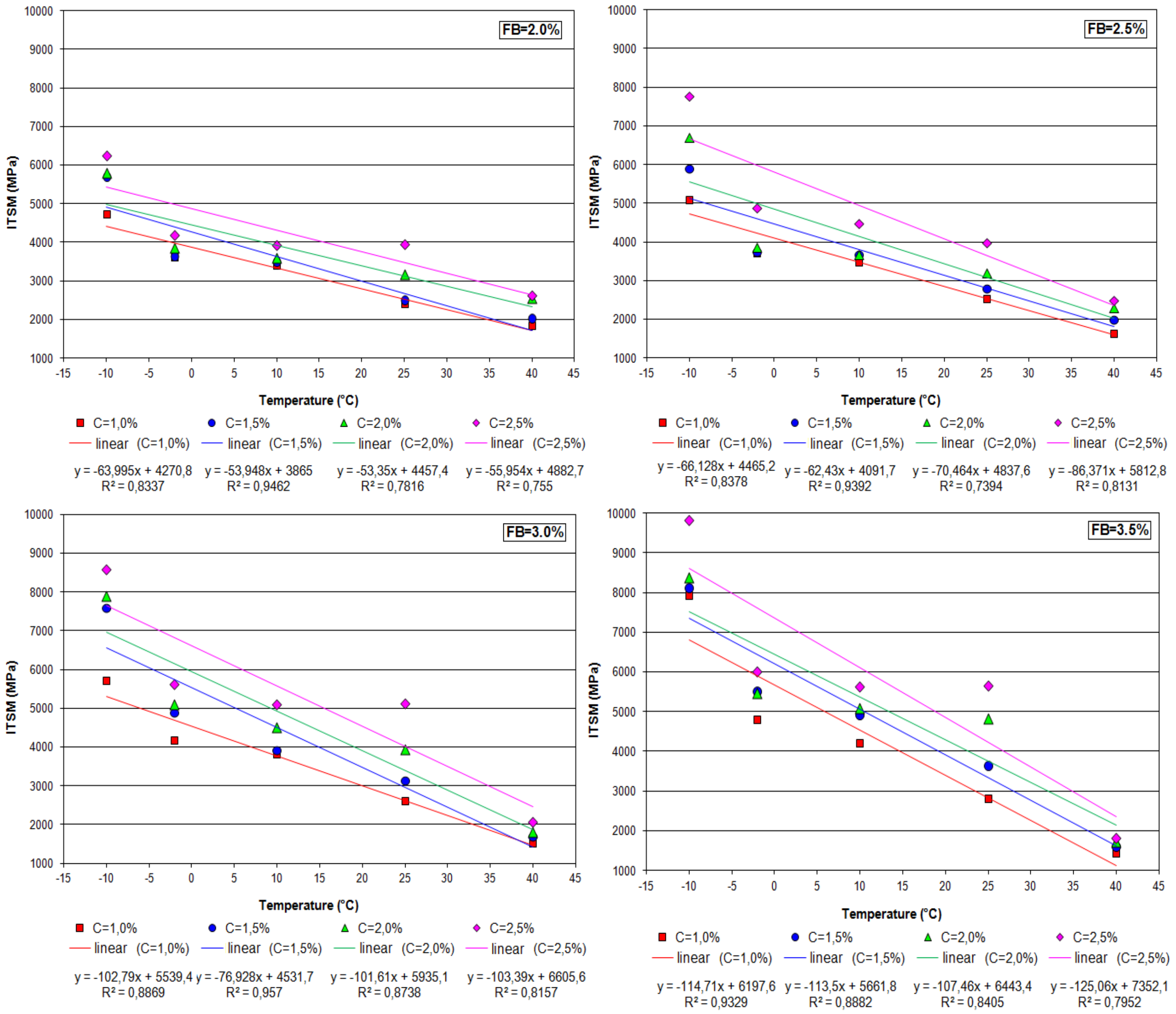


Figure 12 : Relationship between ITSM and the temperature of the recycled mixes with various content of binding agents (FB, C)

Linear regression has been used to analyse the influence of temperature changes on the mean ITSM values of the recycled mixes with different binder contents. The slope of the ITSM-temperature curve increased as the foamed bitumen content increased from 2.0% to 3.5%. Basing on the test results it can be stated that the values of indirect tensile stiffness modulus are significantly higher at low temperatures regardless of the binder content. The increase in temperature (from -10ºC to +40ºC) leads to lower values of the investigated parameter. Moreover, it can be concluded that the increase in cement content reduces susceptibility of the recycled base mixes to high temperature. At foamed bitumen contents of 2.5% and 3.0% in the base mixes a decrease in the impact of increased cement contents at the higher temperature (+40ºC) has been observed.

4. CONCLUSIONS

Basing on the analysis of the test results of the recycled base with foamed bitumen the following conclusions can be drawn:

- the indirect tensile strength (soaked and unsoaked) of the base course materials increases with the increase in foamed bitumen content in recycled pavement material;
- the addition of 2.5% foamed bitumen and 2.0% hydraulic binder (cement) to the base course mixes provides required physical (air void content) and mechanical parameters (ITS_{dry} and ITS_{wet});
- the increase in content of the binding materials (foamed bitumen, cement) in recycled pavement mixes leads to obtaining tensile strength retained (TSR) at the higher level; the water resistance is ensured with 2.0% cement content in recycled pavement which already contains 2.5% of foamed bitumen;

- the foamed bitumen and cement contents in the mixes have a significant influence on the changes of the indirect tensile stiffness modulus; the values of ITSM increased when the bitumen binder and hydraulic binder content increased;
- basing on the test results of indirect tensile stiffness modulus at negative temperatures and after soaking with water it can be stated that the resistance to water, frost and low – temperature cracking during winter is achieved for the recycled mixes;
- the required water and frost resistance according to AASHTO T283 of tested material were obtained by the application of higher content of these binding material (FB_{min}=2.5%, C_{min}=2.0%);
- the water resistance criterion of the recycled base course mixes basing only on the TSR parameter is insufficient and should be broadened to include the proposed AASHTO T283 method

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