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CIVIL ENGINEERING

Evaluation of the pavement performance

M. IWAŃSKI* and A. CHOMICZ-KOWALSKA

Department of Transportation Engineering, Faculty of Civil Engineering and Architecture, Kielce University of Technology,
7 Tysiąclecia Państwa Polskiego Ave., 25-314 Kielce, Poland

Abstract. This paper focuses on evaluation of two laboratory-based methods of compaction of foamed bitumen and bitumen emulsion mixes: impact compaction with a Marshall hammer and static compaction using a hydraulic press. The investigated compaction methods were assessed in terms of their impact on the physical and mechanical properties of produced laboratory specimens, including: air void content, indirect tensile strength before and after conditioning in water (ITS_{dry}, ITS_{wet}), tensile strength ratio (TSR), and indirect tensile stiffness modulus (ITSM) at 0°C, 10°C and 20°C. The statically compacted specimens attained higher levels of mechanical properties and resistance to moisture damage, which was associated with a lower content of air voids in the specimens formed using a hydraulic press. Authors present a calculation showing that a mechanistic design based on the laboratory static press compaction method leads to overestimation of fatigue cracking resistance of the road base.

Key words: Marshall hammer, hydraulic press, road base, full-depth cold recycling technology, foamed bitumen, bitumen emulsion, durability, resistance to moisture damage, diagnosis.

1. Introduction

Over the last several years, serious attention has been given to finding material and technological solutions that would be an answer to environmental protection and sustainability issues in road construction. In line with those well recognized challenges, Radziszewski et al. [1] reported that the Polish program of construction and re-construction of roads required large quantities of aggregates.

A growing interest in cold mix recycling with foamed bitumen stems from the possibilities that this technology provides, which include: the re-use of materials, reduced use of new bitumen and aggregates, and reduced energy intensity of repair works, thus contributing to lowering road maintenance costs. Over the years, the full-depth cold recycling technology with foamed bitumen proved to be a partial solution to most of the aforementioned problems.

To ensure the reliability and safety of engineering structures throughout their service life it is important to control them and determine their current condition [2]. Those goals can be achieved by implementing quality management strategies, which often are realized by means of regular inspections carried out at the design, execution and maintenance stages [3]. However, primarily the expected durability of the rehabilitated structures can be achieved only by introducing a proper structural design and correct execution with a selection of appropriate materials, which usability is maintained by a balance between performance and reliability [4, 5].

Although cold mix recycling with mineral-cement-emulsion (MCE) is the most popular pavement construction technology in Poland, the research carried out at the Kielce University of Technology showed that mixtures with foamed bitumen provide better durability of the road structure under aggressive traffic loads and unfavourable climatic conditions [6-8]. What is more, thanks to the small amount of water (2–3%) contained in foamed bitumen, the base course reaches the required strength parameters quite quickly, which, compared with the bitumen emulsion mix technology, decreases the necessary curing time.

A study developed by Zawadzki et al. [9] and published in 1999 by the Road and Bridge Research Institute, titled: *Technical Requirements for the Construction of Base Course Layers with Mineral-Cement-Emulsion Mixes*, provided two laboratory methods of forming specimens: impact compaction with a Marshall hammer (method I) and static compaction with a hydraulic press (method II). In the first method, the specimens have to be cured for 28 days, whereas the other method lets the specimen to be cured for only seven days, which for practical reasons is a more favourable option from the Contractor's point of view. Many researchers [10–12] have studied the effect of the compaction technique on the properties of bituminous mixtures, but currently in Poland there are no strict requirements relating to the recycled mixes with foamed bitumen for base courses. For the purposes of this research, the procedures adopted by other countries [13, 14] as well as the recommendations of the Technical Specification [15] were used for the conditioning and compaction of cold recycling specimens. This article presents one of the first attempts to assess the influence of the modes of laboratory compaction on the properties of mixes with foamed bitumen in relation to Polish road design practice. Additionally, a comparison with the results acquired on an equivalent mineral-cement-emulsion mix is presented.

*e-mail: iwanski@tu.kielce.pl

2. Materials and methodology

2.1. Binding agents. The mineral-cement-emulsion mix (Emulsion-Mix) was manufactured with the slow-setting cationic emulsified bitumen C60B5R that satisfies the requirements of *EN 13808*. The mix with foamed bitumen (Foam-Mix) was produced using a 50/70 binder foamed in a Wirtgen WLB 10S laboratory plant. The 50/70 bitumen was tested for its conventional and foam-specific properties. The standard tests [16] resulted in: *PG* = 58.7 (0.1 mm) (penetration grade, *EN 1426*), $T_{R\&B} = 51.3$°C (softening point temperature, *EN 1427*), $T_{Fraass}, = -14.3$°C (breaking point temperature, *EN 12593*). The foaming characteristics were measured at 170°C and FWC = 2.5% (*Foaming Water Content*): *ER* = 11.1 and HL = 10 s (foam expansion ratio and half-life respectively, *Wirtgen 2012* [13]).

As required by [9, 15], Portland cement CEM II 32.5 was used as a hydraulic binder in compliance with EN 197-1. Its role is to control the bitumen emulsion breaking time in the Emulsion-Mix [17], ensure uniform dispersion of the foam in the Foam-Mix and improve the strength and resistance to moisture damage parameters of the recycled materials [6, 7].

2.2. Raw materials. In accordance with the recommendations [9, 15], the recycled mixes were produced from a material derived from existing layers of a road pavement:

- reclaimed asphalt pavement (RAP) containing pulverized bituminous pavement layers, 0/25 mm gradation,
- reclaimed stone from mechanically stabilised aggregate base course, 0/31.5 mm gradation.

Additionally, the mix was complemented by virgin 0/4 mm limestone aggregate (satisfying *EN 13242*) to achieve the desired gradation. The 5.1% binder content in the utilized RAP was determined in accordance with *EN 12697-1*.

2.3. Mix design procedure. The principal objective of this study was to evaluate the influence of laboratory compaction methods of recycled cold bituminous mixes on their selected physical and mechanical properties. Two compaction methods were used in accordance with recommendations [9, 15], i.e. method I – impact compaction (the Marshall hammer) and method II – static compaction (hydraulic press).The tests were carried out on two recycled mixes designed for base course, varying in bitumen binder type (Emulsion-Mix, Foam-Mix).

In both mixes, the amount of added binder (FB: foamed bitumen, BE: bitumen emulsion) was 3.0%, whereas the hydraulic binder was fed in the amount of 2.0%. The content of the used binding materials was established based on the authors' experience [6, 7, 16]. The total amount of the bitumen binder in the recycled mixes was 5.5%, which complied with the recommendations [9, 15], where the combined content of the old (derived from the RAP) and the new binder (for the Emulsion-Mix, the new binder is the bitumen after the emulsion break-up) should not exceed 6.0% (m/m) for mixes with 0/31.5 mm gradation. The recycled mix design (Fig. 1) complied with gradation criteria for both cold mixes with FB and BE in accordance with [9, 13].

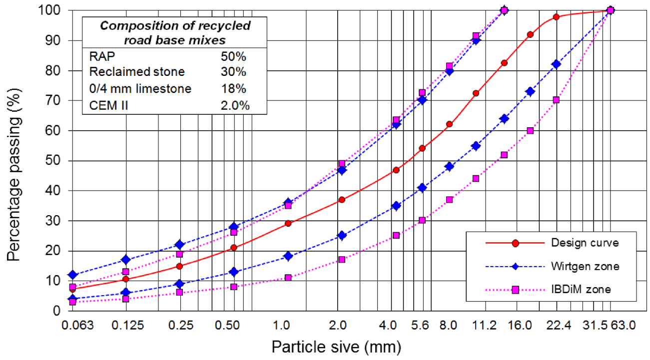

Fig. 1. Gradation of the mineral-cement recycled cold mix for base courses

2.4. Specimen preparation and curing process. Current recommendations [9, 15] followed in Poland at the design and quality control stages of base course construction for recycled foam and emulsion mixes specify two methods for laboratory compaction:

- method I – impact compaction using the Marshall hammer, 75 blows per face,
- method II – static compaction using a hydraulic press with a constant pressure of 100 kN (5 minutes).

The duration of conditioning period of cold mix specimens is dependent on the binder type used. Mixes without cement achieve the maximum strength upon water evaporation, whereas the mixes containing Portland cement reach their designed structural capacity upon the completion of the hydraulic binder setting process. Thus the evaluation of the recycled mixes should in this case take place when their mechanical parameters reach their limit values or when their further increase is insignificant.

In Poland, the curing period for MCE specimens depends on the compaction method and lasts 28 days in the case of the specimens compacted using method I, and 7 days for the specimens compacted using method II. The curing temperature is the same in both cases (20±5°C)The specimens comprising foamed bitumen, regardless of the compaction method used, are stored in moulds for 24 hours at 20°C and then cured at 40°C for 72 hours. This procedure is an accelerated (equivalent to about 30 days) conditioning process adopted by TG2 [14].

The Foam-mix and Emulsion-mix specimens were compacted using both methods (I and II) for comparison. The curing period was adequate and adjusted to the type of the binder used in the recycled mixes.

2.5. Experimental program. The evaluation of the influence of laboratory compaction methods was carried out on recycled base course mixes designed for KR4 traffic (20 year design pavement life of $2\,500\,000 \leq ESAL_{100\ kN} \leq 7\,300\,000$ in accordance with the Polish standards). The compaction modes were assessed in scope of their influence on the following parameters: air void content (V_a, *EN 12697-8*), indirect tensile strength (ITS_{dry}, ITS_{wet}) [13], resistance to moisture damage on the basis of tensile strength retained ratio (*TSR*) [13] and indirect tensile stiffness modulus at 0°C, 10°C and 20°C (*ITSM*, *EN 12397-26* Appendix C).

The parametric analysis was conducted for the following factors:

- *compaction method*: method I (impact), method II (static),
- *type of the mix*: Foam-mix, Emulsion-mix.

Statistical t-tests were performed to determine if those factors (modes of compaction and types of mixes) had a statistically significant influence on the measured specimen properties.

3. Results and discussion

3.1. Compaction effects on air void content. The air void content in the recycled mixes depends on the amount of fines <0.063 mm (including hydraulic binder) and bitumen binder in their composition. Adequate amounts of both components bonded to form bitumen mastic provide the base course with the required levels of voids in the material as well as the air void content related resistance to moisture damage.

The relationship between the air void content and the used compaction method of the recycled mixes is shown in Fig. 2. Table 1 summarises the results of the Student t-tests from the evaluation of factors (among: *compaction method*, *type of the mix*) and their significance on the impact on the distribution of characteristic V_a.

Assessment of the air void contents (Fig. 2) indicates that both mixes were properly compacted reaching the recommended air voids, which according to [9, 15] should be in the range of 9% to 16% for the mixes compacted using the Marshall hammer and in the range of 5% to 12% for the mixes compacted using the hydraulic press. The following relationship was observed: the specimens subjected to static compaction had lower air void contents than those subjected to impact compaction. In addition, regardless of the compaction method used, higher V_a values were recorded for Foam-Mix specimens.

The analysis of the tests results revealed that the *compaction method* had significant influence (a significance level a $\alpha = 0.05$) in the air void content in both evaluated mixes, whereas the *type of the mix* factor was insignificant.

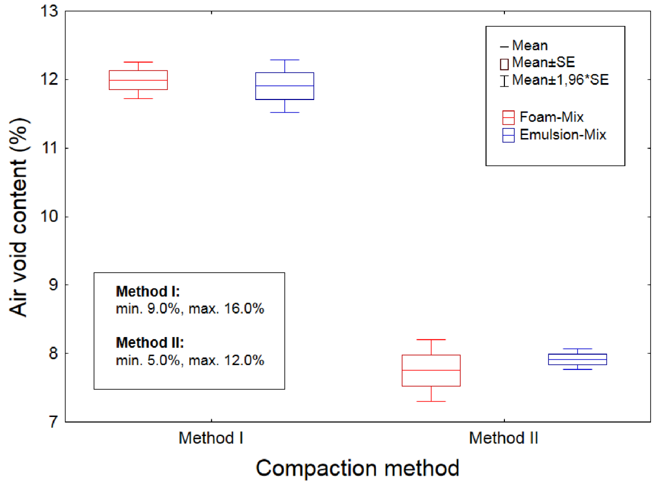

Fig. 2. Box plot for *air void content* variable with *compaction method* as the grouping variable

3.2. Compaction effects on indirect tensile strength and tensile strength retained. Indirect tensile strength is now considered as the basic parameter for estimating optimum binder contents (bitumen and Portland cement) in cold recycled mixes. As recommended in [13, 14], this parameter is determined at a temperature of 25°C on dry specimens (ITS_{dry}) and on specimens conditioned in water for 24 h (ITS_{wet}). The ITS_{wet}/ITS_{dry} ratio is the basis for determining the *TSR* (tensile strength retained), which enables the recycled mixes to be evaluated with respect to their resistance to moisture damage. As the indirect tensile testing is used to establish the binder content, it also indicates the need of using hydraulic binder and its effectiveness in BSM's (Bitumen Stabilised Materials) [13, 14]. Instruction [17] of 2013, the revised version of the rules concerning the design and placement of cold MCE mixes [9] developed by IBDiM in 1999, introduced the requirements concerning the indirect tensile strength values and indirect tensile strength retained values of specimens conditioned in water, but excluded Marshall tests (stability and plastic flow).

Table 1
T-tests results for the statistical significance of the investigated factors (*compaction method*, *type of the mix*) influence on the air void content

T-tests; Grouping: Compaction method (Method I, Method II)/Type of mixture (Foam-Mix, Emulsion-Mix) Group (1): Method I/Foam-Mix Group (2): Method II/Emulsion-Mix								
Comparative groups	Mean (1)	Mean (2)	t-value	*df*	p	N (1)/(2)	Std. Dev. (1)	Std. Dev. (2)
Grouping: Compaction method								
Foam-Mix: (1)-(2)	11.9933	7.75333	15.8565	10	< 0.001	6	0.333686	0.563619
Emulsion-Mix: (1)-(2)	11.9083	7.91667	19.0193	10	< 0.001	6	0.478724	0.187368
Grouping: Type of mixture								
Method I: (1)-(2)	11.9933	11.9083	0.356780	10	0.7287	6	0.333686	0.478724
Method II: (1)-(2)	7.75333	7.91667	−0.67360	10	0.5158	6	0.563619	0.187368

Table 2
T-tests results for the statistical significance of the investigated factors (*compaction method*, *type of the mix*) influence on the outcomes of indirect tensile tests

T-tests; Grouping: Compaction method (Method I, Method II)/Type of mixture (Foam-Mix, Emulsion-Mix)
Group (1): Method I/Foam-Mix
Group (2): Method II/Emulsion-Mix

Variable	Comparative groups	Mean (1)	Mean (2)	t-value	df	p	N (1)/(2)	Std. Dev. (1)	Std. Dev. (2)
				Grouping: Compaction method					
ITS_{dry}	Foam-Mix: (1)-(2)	516.683	576.112	−14.330	10	< 0.001	6	5.73670	8.38349
	Emulsion-Mix: (1)-(2)	490.268	514.922	−2.5639	10	0.0282	6	13.8340	19.0623
ITS_{wet}	Foam-Mix: (1)-(2)	425.690	493.163	−11.363	10	< 0.001	6	10.4723	10.0936
	Emulsion-Mix: (1)-(2)	388.403	435.858	−5.9358	10	0.0001	6	18.4309	6.61762
				Grouping: Type of mixture					
ITS_{dry}	Method I: (1)-(2)	516.683	490.268	4.32039	10	0.0015	6	5.73670	13.8340
	Method II: (1)-(2)	576.112	514.922	7.19755	10	< 0.001	6	8.38349	19.0623
ITS_{wet}	Method I: (1)-(2)	425.690	388.403	4.30853	10	0.0015	6	10.4723	18.4309
	Method II: (1)-(2)	493.163	435.858	11.6300	10	< 0.001	6	10.0936	6.61762

Figure 3 illustrates the distribution of ITS_{wet} and ITS_{dry} and below are shown the computed *TSR* values according to the used compaction method (method I, method II) for the recycled Foam-Mix and Emulsion-Mix. The results of the Student's t-tests carried out to evaluate if the *compaction method* and *type of the mix* factors had significant influence on the distribution of ITS_{wet} and ITS_{dry} are summarised in Table 2.

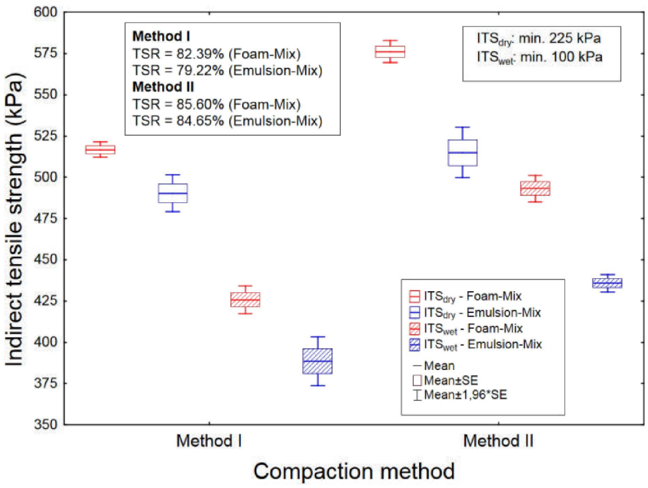

Fig. 3. Distribution of the results of indirect tensile tests carried out on the investigated recycled mixes subjected to different modes of compaction (adequate computed TSR values are shown below)

Analysis of the results indicates that the compaction method and the type of binder (FB, BE) used in the recycled base mixes had a significant effect on the investigated mechanical properties (ITS_{dry}, ITS_{wet}, *TSR*). Compared with the Emulsion-Mix, the Foam-Mix achieved higher *ITS* values measured on both, dry and wet specimens, regardless of the used compaction method. In indirect tensile tests, the Emulsion-Mix samples compacted in a hydraulic press performed better, with an average 5% increase of ITS_{dry} and 12% of ITS_{wet}. Similar results were recorded for the Foam-Mix, but this increase was bigger in magnitude and reached the levels of about 12% and 16% respectively. All of the samples, achieved higher than the minimum required values of ITS_{dry} ($\geq$ 225 kPa) and ITS_{wet} ($\geq$ 100 kPa) [13, 14].

The established values of *TSR*, which are a tool to evaluate the sensitivity of the recycled material to moisture damage, indicate that the foamed bitumen present in the base course mix provides it with the resistance higher than that provided by the Emulsion-Mix. According to [15, 18], the value of *TSR* should be greater or equal to 80%, thus the mineral-cement-emulsion mix subjected to impact compaction failed to meet this criterion (*TSR* = 792%). It can be then concluded that the base course with FB was more resistant to the action of water than the base course with BE. The hydraulic press compaction resulted, on average, in 7% higher Emulsion-Mix *TSR* values and about 4% higher Foam-Mix *TSR* values compared to the specimens subjected to impact compaction.

The analysis of t-test results (Table 2) revealed significant differences (p-$value < 0.05$) between the mean values of the of the investigated properties (ITS_{dry}, ITS_{wet}) for the analysed factors, thus it can be stated that both the mode of compaction and the type of binder had significant influence on the distribution of these characteristics.

3.3. Compaction effects on indirect tensile stiffness modulus. The choice of types and amounts of binding materials depends on the desired properties of the mineral mix, and their appropriate levels provide the mix with predominantly bituminous bonds (flexible base course) or predominantly hydraulic bonds (rigid base course) [17]. The indirect tensile stiffness modulus test is used to evaluate the behaviour and nature of the base course manufactured in cold recycling technology. A low value of *ITSM* may result in an increased deformation susceptibility of the layer, whereas too high values may lead to shrinkage cracking. The tests should be carried out at temperatures of 2°C, 10°C and 20°C to determine the resistance of the mix to low and high temperatures [19].

Table 3
T-tests results for the statistical significance of the investigated factors (*compaction method*, *type of the mix*) influence on the outcomes of ITSM tests at different temperatures

T-tests; Grouping: Compaction method (Method I, Method II)/Type of mixture (Foam-Mix, Emulsion-Mix)
Group (1): Method I/Foam-Mix
Group (2): Method II/Emulsion-Mix

Variable	Comparative groups	Mean (1)	Mean (2)	t-value	*df*	*p*	*N* (1)/(2)	Std. Dev. (1)	Std. Dev. (2)
				Grouping: Compaction method					
ITSM 0°C	Foam-Mix: (1)-(2)	4546.33	5144.17	−18.6259	10	< 0.001	6	71.1299	33.4928
	Emulsion-Mix: (1)-(2)	3217.83	3646.17	−11.2024	10	< 0.001	6	77.7365	52.2395
ITSM 10°C	Foam-Mix: (1)-(2)	4265.67	4483.50	−3.32418	10	0.0077	6	87.8833	134.319
	Emulsion-Mix: (1)-(2)	2591.83	2860.67	−7.42040	10	< 0.001	6	49.1911	73.8611
ITSM 20°C	Foam-Mix: (1)-(2)	3800.83	4062.50	−5.01796	10	0.0005	6	69.5023	107.167
	Emulsion-Mix: (1)-(2)	2273.17	2462.33	−3.65076	10	0.0045	6	92.0813	87.3514
				Grouping: Type of mixture					
ITSM 0°C	Method I: (1)-(2)	4546.33	3217.83	30.88361	10	< 0.001	6	71.1299	77.7365
	Method II: (1)-(2)	5144.17	3646.17	59.13107	10	< 0.001	6	33.4928	52.2395
ITSM 10°C	Method I: (1)-(2)	4265.66	2591.83	40.70986	10	< 0.001	6	87.8833	49.1911
	Method II: (1)-(2)	4483.50	2860.67	25.93246	10	< 0.001	6	134.319	73.8611
ITSM 20°C	Method I: (1)-(2)	3800.83	2273.17	32.43567	10	< 0.001	6	69.5023	92.0813
	Method II: (1)-(2)	4062.50	2462.33	28.35007	10	< 0.001	6	107.167	87.3514

The tests for the indirect tensile stiffness modulus were carried out in the Universal Testing Machine (UTM-25) under the following conditions: test temperatures: 0°C, 10°C, 20°C [20]; rise time: 124±4 ms; deformation level: 5 μm; number of loadings: 5. The values of Poisson ratios were taken depending on the test temperature: $\nu = 0.25$ for 0°C and 10°C and $\nu = 0.35$ for 20°C [21].

Figure 4 illustrates the changes in ITSM values measured in different temperatures (at 0°C, 10°C, 20°C) on samples produced in the two evaluated modes of compaction. Table 3 summarises an analysis of the studied factors (*compaction method*, *type of the mix*) using the Student's t-test of significance.

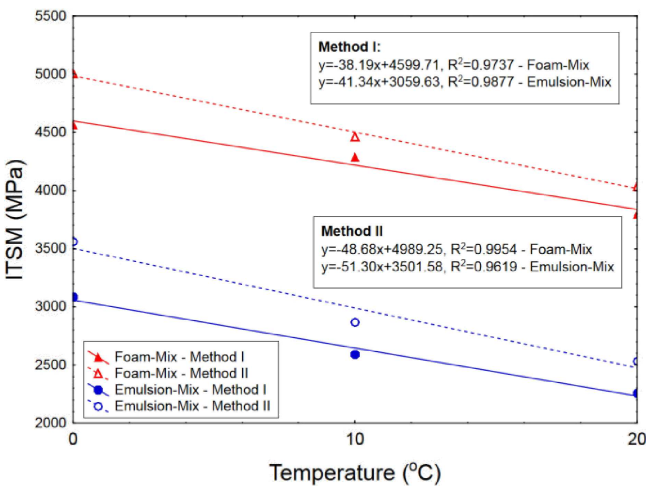

Fig. 4. Relationship between the tests temperature and the *indirect tensile stiffness modulus* of the recycled mix specimens compacted using method I and method II

Higher values of *ITSM* were reported in the specimens with foamed bitumen as a binder, in both modes of compaction. The p-values obtained in the t-tests for the factors under investigation (*compaction method type of the mix*) were by far lower that the assumed level of significance ($\alpha = 0.05$), thus it can be stated that the type of the binder (FB, BE) contained in the recycled mixes had a significant effect on the distribution of the *ITSM* variable regardless of the test temperature.

National and foreign experiences [7, 21–23] indicate that stiffness moduli values decrease with increasing test temperatures. According to German recommendations [18] concerning cold mix base course with foamed bitumen composed of RAP and crushed-stone aggregate (50/50), the value of *ITSM* at a temperature of 25°C should be contained in the range 2500 MPa to 4000 MPa. Based on the indirect tensile stiffness modulus measurements at different temperatures it was possible to observe a lower sensitivity of the Foam-Mix (less steep slope of regression lines) to temperature changes compared with the Emulsion-Mix, in which a higher drop in the *ITSM* values was noted with the temperature increase in both modes of compaction. In addition, a higher difference (increase) in stiffness moduli was observed in both mixes subjected to static compaction compared with those in the mixes subjected to impact compaction.

3.4. Compaction effects on structure of foamed bitumen stabilised materials. Bitumen stabilised materials used in base course layers and produced in cold recycling have a high content of air voids compared with traditional hot bituminous mixtures. As mentioned earlier, air void levels in recycled materials depend primarily on the amount of fines added (<0.063 mm) and the content of binding agents (bitumen binder, hydraulic binder) which combined form mastic. Proper selection of binding agents and their concentrations usually provides the base course with the required content of air voids (tightness) in the processed material and with the related resistance to water damage. For foamed bitumen mixes, Fu *et al.* [24] distinguished three phases (Fig. 5): the aggregate skeleton, the asphalt mastic phase and the mineral filler phase. The process of forming bitumen mastic from the combination of foamed bitumen and mineral fines, with a net-like microstructure has been described in detail in [24]. The structure of mineral-cement-emulsion mixes has been analysed and clarified by Kukiełka [25].

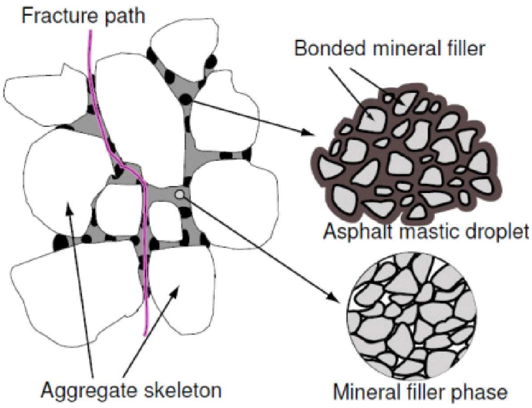

Fig. 5. Conceptual illustration of the microstructure of a foamed asphalt mix (Ref. 24)

The laboratory testing was conducted on the resultant structure (Fig. 6) of compacted material, which is quite complicated due to a large number of contact areas in recycled mixes. The analysis of the macrostructure refers exclusively to the evaluation of geometrical form of the components and their interrelations.

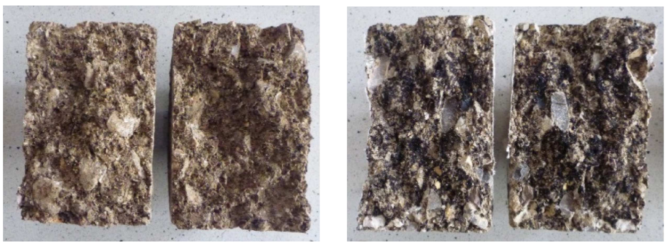

Fig. 6. Fracture face of the Foam-Mix specimen (FB=3%) compacted using Marshall hammer (left) hydraulic press (right)

Analysis of the resultant structure of the compacted material (Foam-Mix) indicates that the specimen preparation method had a clear influence on the fracture path under indirect tensile testing of the recycled mix.

Figure 6 shows a specimen fracture face on which the differentiation is clearly visible. In the statically compacted specimen, the fracture path crosses all the phases, i.e. the aggregate skeleton, the bitumen mastic phase and the mineral filler phase. Whereas in the specimen subjected to the impact of the Marshall hammer, the fracture line skips the aggregate skeleton phase, which makes the specimen fracture face more irregular.

3.5. Predicted pavement fatigue life in scope of different compaction methods used in the design of pavement. The differences in mechanical properties of samples obtained using different compaction methods may be a cause of significant pavement design errors. Polish engineers use widely the Asphalt Institute fatigue criterion from the Mechanistic-Empirical Pavement Design Guide (MEPDG), which is shown in (1)–(3):

$$N_f = 18.4 \cdot C \cdot (6.167 \cdot 10^{-5} \cdot \varepsilon_r^{-3.291} \cdot |E*|^{-0.854}), \quad (1)$$

$$C = 10^M, \quad (2)$$

$$M = 4.84 \cdot (V_b/(V_b + V_a) - 0.69), \quad (3)$$

where N_f – fatigue cracking life (with 20% of road surface cracked), ε_r – horizontal tensile strains at the bottom of bituminous layers, $E*$ – stiffness modulus of the bituminous layer, V_b – volumetric binder content (%), V_a – air void content (%).

Recently, the new AASHTO 2004 criterion (4) for predicting pavement fatigue cracking has been adopted in the Polish pavement design practice [26]. The calculated number of load repetitions is associated with damage $D = 1$ for the considered bituminous layer. By calculating the actual fatigue damage using the Miner's rule it is possible to predict the fatigue bottom-up cracking in percent of total lane area through the transfer function (5).

$$N_f = 7.3557 \cdot 10^{-6} \cdot C \cdot K_1' \cdot \varepsilon_r^{-3.9492} \cdot E^{-1.281}, \quad (4)$$

$$FC_{bottom} = 100/(1+\exp(-2 \cdot C_2' + C_2' \log_{10}(D \cdot 100))), \quad (5)$$

where $C_2' = -2.40874 - 39.748 \cdot (1 + h_{ac}/2.54)^{-2.856}$, K_1' – parameter dependant on the thicknass of bituminous layers, h_{ac} – thickness of bituminous layers.

An analysis was carried out to evaluate the impact of the compaction method used in the process of full depth reclamation (FDR) pavement design with foamed bitumen. Figure 7 shows a layout of structural layers from an actual road section rehabilitated using full depth recycling with foamed bitumen. The stiffness moduli and further properties of the Foam-mix road base layer presented in Table 4 correspond to the results obtained in the hereby presented research. The "*Guide for Mechanistic...*" [27] states that bitumen stabilized granular materials designed using a compaction device and produced in a controlled manner should be, in scope of the mechanistic-empirical design, treated as a HMA base material. Thomas and May [28] showed that the durability of an emulsion stabilized full depth reclamation layer can be succesfully predicted with the standard equations from the MEPDG. What is more, Kukiełka [25] has thorougly tested emulsion treated FDR mixes for their fatigue performance, claiming that under some assumptions such layers can be incorporated into the mechanistic-empirical method alike to HMA. Having this in mind and assuming that the fatigue performance of Foam-Mix would resemble that of emulsion treated FDR layer, the calculations of fatigue cracking life were carried out at the bottom level of the Foam-Mix layer.

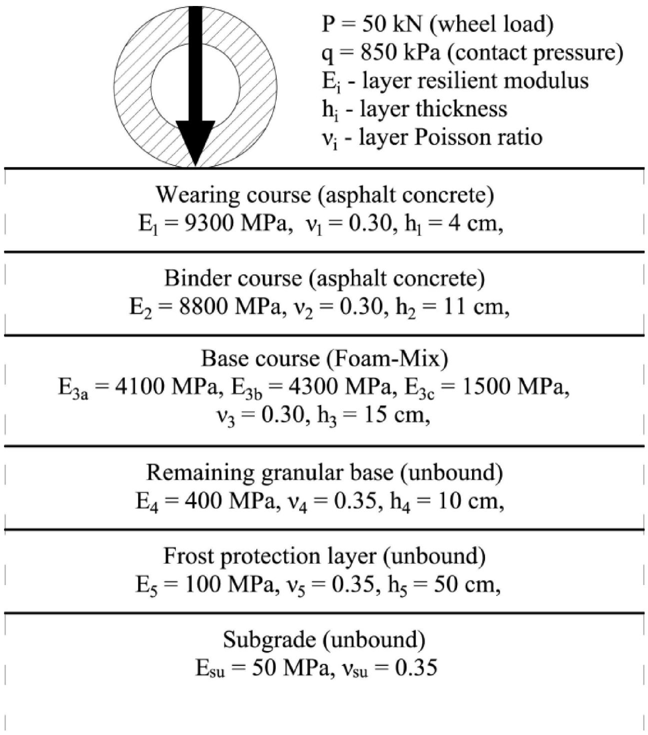

Fig. 7. Structural layers of a test section for fatigue life calculation at 13°C (E_{3a} – stiffness of mixture after impact compaction, E_{3b} – after static compaction, E_{3c} – after base course fracturing)

As it is shown in Subsecs. 3.1 and 3.3, the compaction method had significant influence on the resilient modulus and air void content of the mixture. Compared to impact compaction, the air void content obtained by static compaction was about 4 percentage points lower. Also the resilient modulus was found to be 200 MPa less in the samples compacted using the impact method, which is a relatively small but still significant difference. Both of those measured characteristics are input parameters for the mentioned fatigue cracking criterion, therefore their correct assessment is essential to predict the pavement fatigue life.

The two considered cases correspond to a situation where the engineer relies on the results obtained by either impact or static compaction. The strains acquired using the multilayer elastic theory indicate that the difference in the stiffness moduli obtained in the different compation methods is small and may be considered insignificant. However the overall assessment of cracking fatigue life of the pavement showeda major disparity in the evaluated cases. The calculations carried out through the Asphalt Institute criterion (1) and the material properties acquired in static compaction lead to an significant increase in predicted fatigue life (approx. 3 times greater when compared to the results from the dynamically compacted material). In line with these results, the AASHTO 2004 criterion (4), (5) predicted similarly less bottom-up cracking.

Additionally, the fatigue life calculation was carried out for the two stages of the reclaimed Foam-mix road base: before and after fracturing, using the two mentioned fatigue life criterions. The results show that variation in fatigue life prediction in those two service stages is rather small in the considered case.

Taking into account the fact that the properties of the cored samples from the test section resembled very well the test specimens fabricated by impact compaction, it can be assumed that the design based on statically compacted specimens would lead to overestimation of the cracking fatigue life of the pavement incorporating FDR foam stabilised material.

Table 4
Fatigue life calculation

Parameter	Compaction Method	
	I	II
FDR foam mixture properties		
Bitumen content (% by mass)	5.50%	
Bitumen content (% by volume)	13.40%	
Air void content (% by volume)	12%	7.80%
Stiffness modulus before fracturing at 13°C [MPa]	4100	4300
Stiffness modulus after fracturing[a] [MPa]	1500	1500
Fatigue life calculation before fracturing		
Horizontal strains: ε_r	$8.11 \cdot 10^{-5}$	$7.94 \cdot 10^{-5}$
Asphalt Institute: N_f	4 387 514	14 487 549
AASHTO 2004: $FC_{\text{bottom at 7 500 000 axles}}$	6.03%	1.80%
Fatigue life calculation after fracturing		
Horizontal strains: ε_r	$1.12 \cdot 10^{-4}$	$1.12 \cdot 10^{-4}$
Asphalt Institute: N_f	3 610 760	11 581 407
AASHTO 2004: $FC_{\text{bottom at 7 500 000 axles}}$	5.89%	1.79%

[a] values in accordance to [26]

4. Conclusions

It was observed that the mode of compaction had significant influence on the physical and mechanical properties of the recycled bitumen foam and emulsion mixes. The statically compacted specimens had lower air void contents and higher volumetric density. It is presumed that during impact compaction the energy transferred by the hammer is attenuated by liquids present in the mixes, which by absorbing a fraction of that energy, resulting in decreased volumetric density and increased air void content in the specimens [22].

The detailed analysis of the test results concerning the recycled base course with foamed bitumen and bitumen emulsion and the evaluated compaction methods led to the following conclusions:

- compared with the Emulsion-Mix, the foamed bitumen mix had higher indirect tensile strength values in both unsoaked (ITS_{dry}) and soaked (ITS_{wet}) tests regardless of the compaction method;
- recycled base mix specimens subjected to static compaction had lower air voids contents and better mechanical parameters (ITS_{dry}, ITS_{wet}, *ITSM*) than those subjected to the blows of the Marshall hammer;
- analysis of the Foam-Mix structure revealed a clear variation in the fracture path propagation under indirect tensile testing; in the specimens subjected to static compaction the fracture path propagated through all the phases, whereas in the specimens subjected to impact compaction the fracture path bypassed the strong aggregateskeleton phase;
- the foamed bitumen binder in the recycled mixes contributed to the improvement in their resistance to moisture damage compared with the mixes containing bitumen emulsion, regardless of the compaction method;
- the measurement of the indirect tensile stiffness modulus at various temperatures revealed a lower sensitivity of the Foam-Mix to temperature change compared with the sensitivity of the Emulsion-Mix, regardless of the compaction method used.

Based on the results and conclusions, it can be stated that the Marshall hammer compaction is better suited for the design and evaluation of the FDR cold mixes. The authors' field experience show that the volumetric properties acquired through in situ compaction are similar to those produced in impact compaction. Although the differences in other measured properties ($ITS_{dry/wet}$, *TSR*, *ITSM*) were statistically significant, the magnitude of this variation was rather small and could be considered negligible in many cases. Therefore it can be stated that the main distinction in the results from the samples compacted by the means of the considered methods lies in the volumetric properties, which constitute the performance of any bitumen stabilized layer. It can be said that the decision to rule out the static compaction method from the new guidelines for MCE mixes was in line with those conclusions. What is more, the mechanistic-empirical calculations shown that the adoption of mix properties from statically compacted samples of the considered FDR mixes may lead to a significant overestimation of the pavement fatigue life. However, it must be mentioned that the static compaction method is very convenient when testing the actual field materials, especially bitumen stabilized mixes with hydraulic binders. The use of a hydraulic press (thanks to its simplicity and mobility) permits compaction of the sample materials directly on site, bridging the issue of hydraulic binder setting time.

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