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Research paper

Analysis of the compactibility of bituminous mixtures for reflective crack relief interlayers (RCRI)

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Abstract: The physical properties determining the strength parameters of bituminous mixtures are strongly influenced by the processes of placement and compaction. The effectiveness of this process depends on the compactive effort and is directly related to the mixture temperature. This research focused on the assessment of compactibility of mixtures designed for reflective crack relief interlayers (RCRI) which, in most cases, are applied in thin layers. The materials analysed for compactibility in this research included AC – asphalt concrete, AC AF – asphalt concrete "anti-fatigue", SMA – stone mastic asphalt and SMA-MA – stone mastic asphalt rich in bitumen mastic. The gyratory compactor method was used to determine the compaction slope K, the locking point LP and the compaction densification index CDI. All the tested mixtures were fine-graded, i.e., contained grains up to 8 mm in diameter, each mixed with a different type of bituminous binder. The values of CDI show a substantially greater input of energy required for compaction of high-polymer modified mixtures, as compared to mixtures of the same design, yet containing the 50/70 bitumen. Locking point analysis showed that SMA and SMA-MA mixtures attain 98% relative compaction before reaching the locking point at which the aggregate skeleton starts to resist further compaction. This is quite the opposite as with the AC and AC AF mixtures. Among the tested mixtures the best compaction behaviour was observed in the case of SMA-MA 8 50/70, and this over a wide range of working temperature (100–160°C) and pressures (150 kPa, 600 kPa). The design of the mixture SMA-MA as an anti-fatigue layer assumes an increase in the content of filler and binder, as compared to conventional SMA. This composition is bound to reduce the resistance to compaction, i.e., provide a better compaction behaviour as compared to a conventional SMA mixture.

Keywords: bottom asphalt layer, compactibility, gyratory compactor, locking point, stone mastic asphalt

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1. Introduction

In designing pavement structures, we try to reduce the levels of stress and strain at the bottom of bituminous courses and postpone the occurrence of reflective cracking, the latter in the case of semi-rigid structures. Stress and strain reduction significantly correlated with a pavement thickness. Various measures designed to increase the fatigue life of bituminous pavements and postpone the initiation and propagation of reflective cracks have been invented starting from 1960s or earlier [1–4]. Besides the widely known technologies designed to mitigate deterioration of pavements, i.e., geosynthetics, shock absorbing membrane interlayer (SAMI) cracking resistant thin asphalt interlayers are becoming a popular measure. These bituminous mixtures with crack mitigation properties, generally fine-graded, are placed as an interlayer on a deteriorated or jointed rigid layer of pavement to control bottom-up propagation of cracks to the upper bituminous courses yet to be placed. To act as a deformable membrane capable of absorbing and dissipating of stress it should feature the lowest possible void content (ca. 1–2%), a high amount of binder (measured by volume), fine grading, adequate thickness (ca. 20–30 mm) and a superior fatigue and tensile performance over a wide temperature range [5]. These requirements are satisfied by fine-graded bituminous mixtures containing binders, highly polymerised or rubberised (i.e., with addition of crumb rubber) used so far for the asphalt bottom asphalt layers designed to improve fatigue behaviour of the pavement as a whole. AC AF mixture, i.e., asphalt concrete for bottom layers containing 5 mm minus or 8 mm minus aggregate, 10–15% filler and a high amount of binder (8–15%) is a good example of such bituminous mixtures [1, 2, 4]. The AC AF layer concept was implemented by Polish Research Institute (IBDiM) in terms of the first perpetual asphalt pavement design in Poland [6]. Among unconventional materials used in this application we can mention SMA-MA, i.e., SMA mixtures containing more mastic asphalt, so far used primarily as an additional protective layer on bridges [5, 7]. It was also used as a reflective crack relief interlayer (RCRI) during renewal of DW 102 highway in Poland [8]. Combining the advantages of MA gussasphalt, conventional mastic asphalt and SMA mixture, SMA-MA may be good a good alternative measure to mitigate reflective cracking in pavements.

Small thickness of such layers (20–30 mm) means a lower thermal capacity resulting in a faster drop of temperature during compaction due to the action of external factors including wind, water, cold substrate [9]. It is therefore advisable to perform compaction at temperatures at which the viscosity of the bituminous binder falls in the range of 2–20 Pa·s [10]. In the case of thin layers this means a very small time window for compaction, which should start right after the screed of the asphalt finisher. Therefore, impermeability, workability and ease of compacting (compactibility) must be considered as important criteria in assessment of hot mix asphalt (HMA) for RCRI layers. Compaction also increases the stiffness modulus, strength and water and freeze-thaw resistance of the completed course of pavement [11]. It has been confirmed by experiments that the degree of compaction of bituminous mixtures depends strongly on the parameters of the material, including grading, maximum size of aggregate particles, type and amount of the bituminous binder, temperature of the mixture during compaction and thickness of the produced layer [12–17]. Also the equipment and weather factors have a considerable bearing on the effectiveness of the process of compaction.

The conditions during placement of HMA layers significantly influence the strength parameters of the whole pavement structure [18–22]. The mixture compactibility should be assessed at the design stage. It is important that laboratory compaction reflects the final effect of the compaction process during placement of the mixture on site.

2. Compaction methods

In this research the samples were compacted by means of gyratory compactor as per standard [21]. The following parameters of the compaction process taking place in the gyratory compactor:

- vertical pressure – 150 kPa and 600 kPa,
- number of gyrations (n_g) – 200,
- internal angle – 1.16 ± 0.02°,
- speed of gyration – 30 rpm,
- test temperature – 100°C, 130°C, 160°C,
- sample diameter – 100 mm.

The lab test data were plotted on the graphs representing the relationship between the bulk density (or air void content) and the compactive effort (Fig. 1). Due to a large variety of compaction methods, different indicators of the compaction characteristics of the mixture are in use. The most widely used parameters include the slope of the compaction curve K, compaction densification index *CDI* or the Transportation Densification Index *TDI*, all determined with the gyratory compactor [23–29].

The results of the laboratory compaction were analyzed in terms of the $\%G_{mm}$ (percentage of maximum specific gravity achieved at different levels of gyrations: $\%G_{mm}$ at N_{ini} (initial number of gyrations, and $N_{\max}$ (maximum number of gyrations). Determination of the air void content in relation to the number of gyrations n_g gives this method an advantage over other laboratory methods used to determine compactibility of bituminous mixtures and allows easy determination of K as per [28] using the following Eq. (2.1):

$$v\left(n_g\right) = v\,(1) - \left(K \times \ln\left(n_g\right)\right) \tag{2.1}$$

where: n_g – number of gyrations, $v(n_g)$ – air voids after n_g gyrations, $v(1)$ – air voids after the first gyration, K – compaction slope.

Parameter K gives the slope of the approximation curve for the semi-log relationship between the air voids and the number of gyrations (n_g). A higher value of K (absolute value at ln) indicates a faster rate of change in the air voids, i.e. easier compaction of the mixture. The weak point of this method is that the application of K for assessment of mixture compactibility is limited to comparisons and mixtures with a similar initial air void content.

The other parameter, i.e. *CDI* which is obtained from the surface area on the gyratory compaction plot [29]. *CDI* of a bituminous mixture is based on the compaction energy index (*CEI*) [29], calculated as the surface area delimited by the curve from the top and 8-th cycle of compaction and 8% (v/v) air void content from the sides. The lower the value of *CDI* the greater input of energy is needed to achieve the desired compacted density. TDI, in turn,

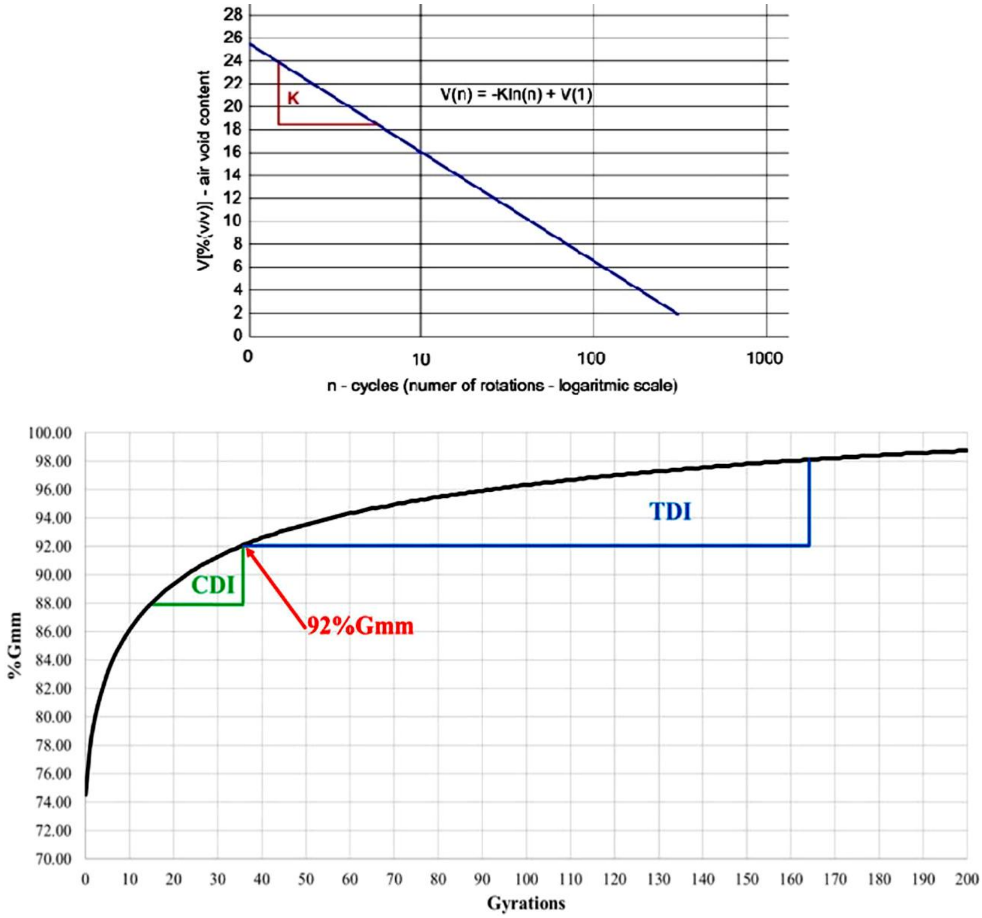

Fig. 1. Compaction curve of bituminous mixture on a gyratory compactor. Determination of the values of *K*, *CDI* and *TDI* [27]

indicates the resistance of the placed mixture to post-compaction by traffic during pavement operation. It is defined as the surface area on the gyratory compaction plot delimited by the curve from the top, and 2% and 8% (v/v) air voids from the sides.

Gyratory locking point (*LP*) is yet another parameter derived from the gyratory compaction curve [30]. It was first defined by William J. Pine [31] as a point on the envelope curve above which the aggregate particles interlock and the skeleton formed in this way resists further compaction. This locking point concept has been elaborated over time [32, 33] and the 2-2-3 method is now believed to provide the best definition, in which the locking point is defined as the first gyration of a set of three gyrations of h = const. preceded by two groups of two gyrations of h = const. [30]. *LP* determination with the 2-2-3 method is presented in Table 1 below.

Table 1. Locking points obtained for SMA MA 8 PMB 65/105-80

Number of gyrations $[n_g]$	Specimen height [mm]
66	101.1
67	101.1
68	101.0
69	101.0
70	**100.9**
71	100.9
72	100.9

3. Materials

Six types of bituminous mixtures were laboratory tested for compactibility, including three asphalt concrete mixtures (including mixtures for bottom asphalt layers – AC AF) and three SMA mixtures (including mixtures with an extra amount of mastic asphalt designated SMA-MA). The mixtures under analysis contained different types and amounts of bituminous binder (plain or PMB – polymer modified asphalt). A specimen cross-section is shown in Fig. 2 and Fig. 3 below.

Fig. 2. Cross-section through a specimen of AC AF 50/70 mixture

Fig. 3. Cross-section through a specimen of SMA-MA PmB 65/105-80 mixture

Selected parameters of the tested mixtures are given in Table 2. The gradation curves are displayed in Fig. 4 below.

Table 2. Mixture design data of HMA

Type of mix	Type of bitumen	Gradation [%]		Filler [%]	Bitumen [%]	Mastic (Filler+Bitumen) [v/v]	Richness modulus *K*	VMA [%]	VFB [%]
		> 2.0 mm	< 2.0 mm						
AC AF 8	50/70	44	56	10	7.8	27.8	5.29	21.0	89.1
	PMB 65/ 105-80								
AC 8 S	50/70	53	47	7.5	6.0	20.6	3.79	15.5	89.9
SMA-MA 8	50/70	70	30	12	9.2	33.7	6.39	23.4	96.0
	PMB65/ 105-80								
SMA 8	50/70	72	28	10	7.2	26.7	4.31	18.5	88.2

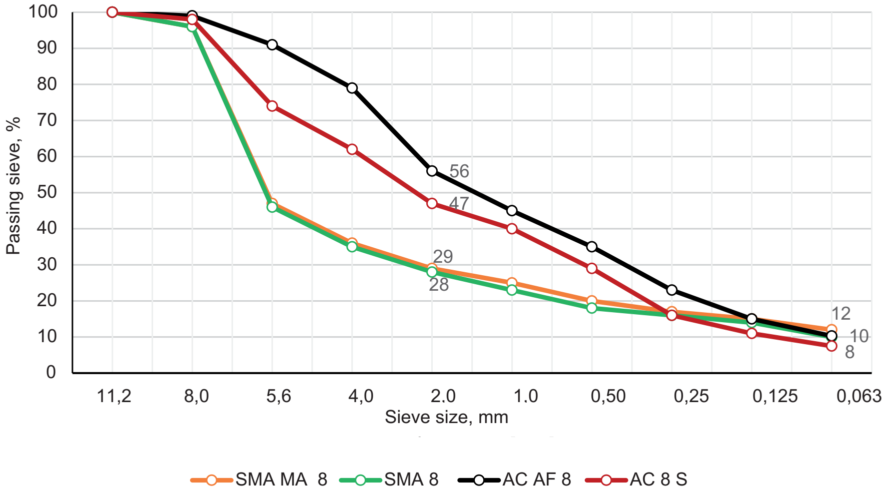

Fig. 4. Gradation curves of the tested mixtures

4. Test results

The compactibility analyses were carried out on six bituminous mixtures subjected to compaction at different temperatures and pressures. The temperature range of the beginning and end of effective compaction, where the viscosity of the asphalt binder is between 2–20 Pa·s, is represented in the test by the temperature of 130°C. In addition, the scope of the tests was extended to include temperatures of 100°C and 160°C to simulate the “in-situ” conditions prevailing during paving. The criteria so adopted make it possible to assess the susceptibility of the mixture to compaction under other than optimum paving conditions. The process temperatures for asphalts are given in tabular form (Tab. 3).

Table 3. The temperature range of effective compaction

	Bitumen 50/70	Polymer Modified Bitumen 65/105-80
Temperature of the beginning of effective compaction	≤ 140°C	≤ 150°C
Temperature of the end of effective compaction	≤ 110°C	≤ 120°C

The tested mixtures must feature low permeability and hence compaction defined by the air voids corresponding to min. 98% theoretical density is considered satisfactory. Table 4 shows how this requirement was satisfied in different test conditions and the mixtures which attained the required density are highlighted by ✓ sign. × indicates that the requirements are not achieved.

Table 4. Compaction compliance matrix against job mix formula (JMF) parameters

Type of mix	Test conditions					
	T = 100°C		T = 130°C		T = 160°C	
	c = 150 kPa	c = 600 kPa	c = 150 kPa	c = 600 kPa	c = 150 kPa	c = 600 kPa
AC AF 8 50/70	×	×	×	×	✓	✓
AC AF 8 PMB65/105-80	×	×	×	×	✓	✓
AC 8 S 50/70	×	×	×	✓	×	✓
SMA-MA 8 50/70	✓	✓	✓	✓	✓	✓
SMA-MA 8 PMB65/105-80	×	✓	×	✓	×	✓
SMA 8 50/70	×	✓	×	✓	×	✓

The data in Table 4 show that SMA-MA 8 mixtures containing 50/70 paving grade bitumen achieve the desired compaction over a wide temperature range, i.e. 100–160°C.This translates to a longer effective time window for compaction and a lower sensitivity to temperature variations, in comparison to the other bituminous mixtures. In addition, SMA-MA 8 50/70 requires less input of energy, as evidenced by a lower contact pressure of c = 150 kPa (as comparted to the typically encountered value of c = 600 kPa). At 130°C and c = 600 kPa AC AF would not achieve the desired compaction, as SMA and SMA-MA would. Therefore, T = 160°C and c = 600 kPa may well be considered optimum compaction conditions for all the mixtures under analysis. For these parameters all the tested mixtures satisfied the compaction (air voids) requirement of JMF. Subsequent analyses were conducted for the mixtures compacted at T = 130°C and T = 160°C and the same pressure of c = 600 kPa and the other mixtures were left out.

The parameters used to assess the compaction characteristics and effectiveness of the compactive effort were the slope of the compaction curve K, CDI and LP.

4.1. Compaction slope *K*

A semi-log graph of the percent air voids and number of gyrations was plotted to derive the value of K for the tested AC AF mixtures. As prescribed by the standard [28] the value of K should be obtained for the best approximation of the experimental data. For the tested AC AF mixtures the test data were approximated by linear regression analysis for the number of gyrations of $n_g = 20$. The results are represented in Fig. 5 and given in Table 5 below.

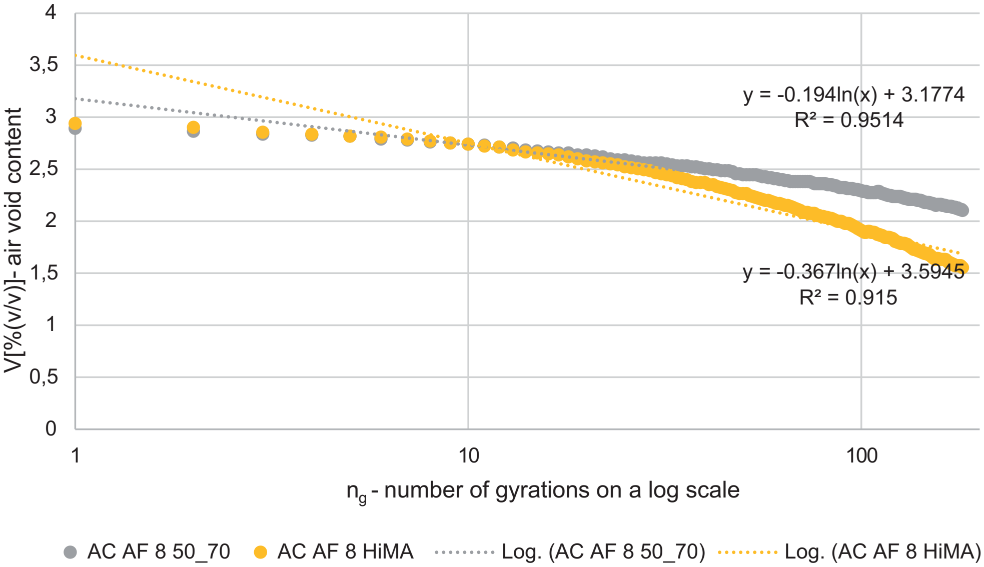

Fig. 5. Compaction slope K for the tested AC AF mixtures ($T = 130$°C, $c = 600$ kPa)

Table 5. K values for the tested AC AF mixtures

Type of mix	Compaction conditions					
	130_600			160_600		
	K	$v(1)$	R^2	K	$v(1)$	R^2
AC AF 8 50/70	0.19	3.2	0.95	0.25	2.3	0.87
AC AF 8 PMB 65/105-80	0.37	3.6	0.92	0.37	2.7	0.91

For the tested SMA-MA mixtures the test data were approximated by linear regression analysis for the number of gyrations of $n_g = 30$. The results are represented in Fig. 6 and given in Table 6 below.

The air voids after the first gyration $v(1)$, derived from the linear regression relationships fell within the ranges of 0.86–3.6% ($T = 130$°C, $c = 600$ kPa) and 2.3–5.5% ($T = 160$°C,

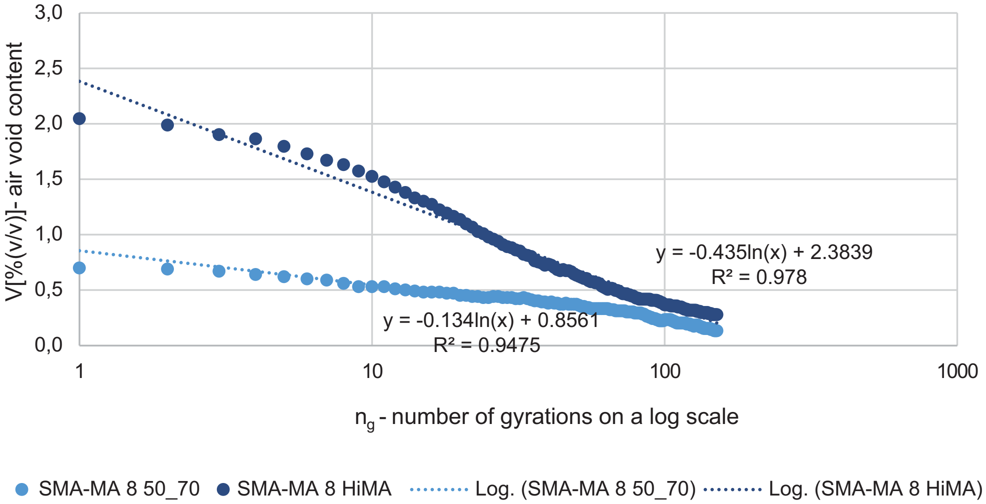

Fig. 6. Compaction slope for the tested SMA-MA mixtures (T = 130°C, c = 600 kPa)

Table 6. K values for the tested SMA MA mixtures

Type of mix	Compaction conditions					
	130_600			160_600		
	K	$v(1)$	R^2	K	$v(1)$	R^2
SMA-MA 8 50/70	0.13	0.86	0.95	0.74	2.3	0.99
SMA-MA 8 PMB65/105-80	0.44	2.38	0.98	1.21	5.5	0.98

c = 600 kPa). Based on Fig. 3 and Fig. 4 it is evident that an error free analysis could not be made due to the big difference in value between the initial air voids. The values of K indicate that an increase in the temperature improves the compaction behaviour of the tested mixtures, as indicated by higher values of K, particularly evident in the case of SMA-MA. Comparing the values of K we see that SMA-MA mixtures feature a better compactibility.

However, the method based on the value of K has certain pre-conditions that limit its application. As one of these pre-conditions is a similar value of $v(1)$ for all the analysed mixtures. This makes the comparison of the tested mixtures problematic since the value of $v(1)$ varies strongly even for mixtures of the same type, for example from 0.86% to 5.5% for SMA-MA. Also the K values obtained for the mixtures including polymer modified bitumen are questionable being much higher than those of the mixtures containing 50/70 bitumen. This should have resulted in a better compactibility of the former, which was not the case. Hence, it was decided to use *LP* and *CDI* for assessment of the mixture compactibility.

4.2. Gyratory locking point (*LP*)

The locking point, defined as the number of gyrations after which the increase in density slows down and resistance to compaction becomes evident. Locking point is based on the concept of aggregate skeleton composed of large grains with smaller grains in between which develops in the compaction process and resists further compaction after the grains have interlocked. The aggregate skeleton locking process is different for different mixture and depends on the type of bituminous binder used. In this research *LP* was determined using the 2-2-3 method and marked on the compaction curve where the effectiveness of compaction clearly falls, the air voids stabilise with no significant increase in density as a result. Figs. 7, 8 show *LP* values for the tested mixtures at T = 130°C a T = 160°C and c = 600 kPa. The number of rotations after which the mixtures attain 98% relative compaction (P98) is given in addition.

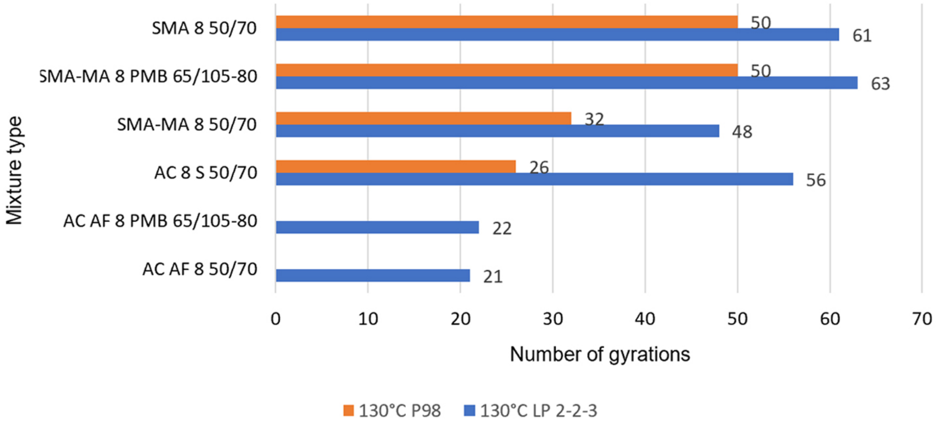

Fig. 7. *LP*s and P98s for the tested mixtures at T = 130°C

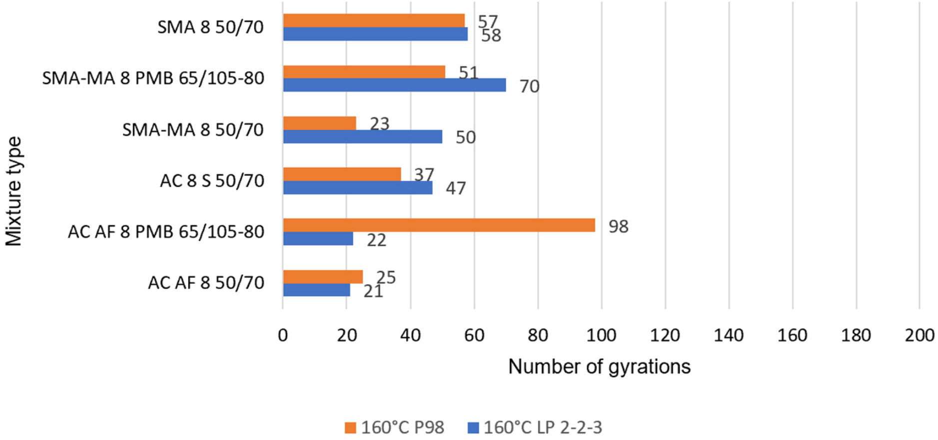

Fig. 8. *LP*s and P98s for the tested mixtures at T = 160°C

The resistance to compaction defined by the number of gyrations at LP 2-2-3 occurs earliest in AC AF mixtures. This compaction behaviour was observed at the test temperatures of $T = 130°\text{C}$ and $T = 160°\text{C}$. At the test temperatures the AC AF mixtures did not reach 98% of the specified air voids when aggregate skeleton locking occurred. The situation is quite the opposite with SMA-MA mixtures. These mixtures reach the desired compaction before locking. Therefore, the specified air voids can be reached in the case of SMA-MA mixtures by the compactive effort of the asphalt finisher and a few passes of a roller. In practical terms, the desired performance parameters can be achieved quite easily. In case *LP* precedes P98, much more compactive effort may be required to reduce the air voids down to the required level. Vibratory compaction may become necessary in the case of AC AF mixtures, especially at low placement temperatures.

4.3. Compaction Densification Index CDI

CDI is a common indicator for assessment of the compatibility of bituminous mixtures. Bitumen rich fine-graded mixtures used for reflective crack relief layers (and bottom asphalt layers) reach the bulk density corresponding to 92% of the maximum theoretical specific gravity (G_{mm}) during the first four gyrations (1–4) making the area between the 8-th gyration and the gyration corresponding to $G_{mm} = 92\%$, as prescribed by the *CDI* determination method, either very small or undeterminable at all. After analysing the compaction values at *LP* and considering the requirement to minimise the air voids in the bottom asphalt layers, a modified *CDI* determination method was adopted in this research. The boundaries of surface area under the compaction curve were taken at the 8-th gyration and the gyration of 98% relative compaction, thus obtaining the compactive effort delivered by rollers. The modified method of *CDI* determination is illustrated in Fig. 9 below and conventionally marked *CDI**.

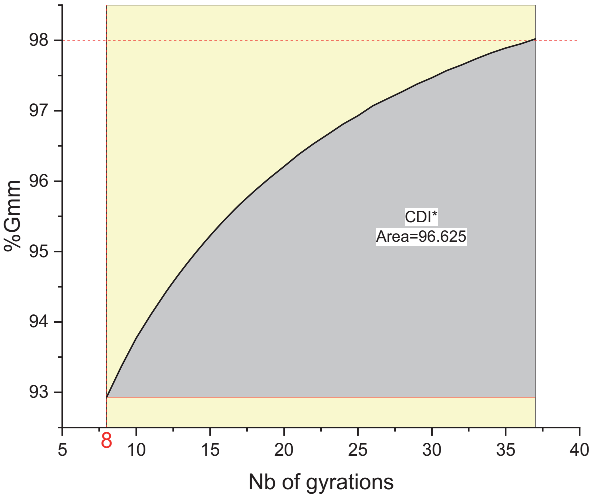

Fig. 9. Determination of CDI for bitumen rich fine-graded mixtures compacted in a gyratory compactor

The literature gives the 2% air void content as the limit value from the point of view of resistance to plastic deformation. However, the cracking mitigation interlayers made of AC AF and SMA-MA are placed on the bottom of bituminous courses where the zone of plastic deformations is limited or non-existent. In addition, considering their role in the pavement structure (improvement of fatigue behaviour and control of reflective cracking) these mixtures are specified with the lowest possible air voids.

The same as in the previous analysis also here the test mixtures compacted at $T = 130°\text{C}$ and $T = 160°\text{C}$ and the pressure of $c = 600$ kPa were considered. Except for the AC AF mixtures compacted at 130°C, all these mixtures reached the specified compaction in the pre-determined test conditions. The values of modified *CDI* are given in Table 7 below. For AC AF compacted at 130°C the value of *CDI* was calculated between the 8-th and 200-th gyrations, even though the required compaction was not achieved in this range.

Table 7. CDI values of the tested bituminous mixtures

Type of mix	$CDI_{130/600}$	$CDI_{160/600}$
	$T = 130°\text{C}$, $c = 600$ kPa	$T = 160°\text{C}$, $c = 600$ kPa
AC AF 8 50/70	346.14$^{1)}$	42.58
AC AF 8 PMB65/105-80	424.80$^{1)}$	163.19
AC 8 S 50/70	47.70	96.63
SMA-MA 8 50/70	96.14	48.79
SMA-MA 8 PMB65/105-80	228.23	237.47
SMA 8 50/70	236.8	308.92

$^{1)}$ Surface area limited by $n_g = 200$

Due to a strong aggregate skeleton conventional SMA mixtures feature a higher than asphalt concrete resistance to compaction. This is indicated by the values of $CDI_{130/600}$ and $CDI_{160/600}$.

The mixtures SMA-MA, in turn, contain an extra amount of filler and bituminous binder, as shown in Table 2. The same applies to the AC AF mixture. The resulting mastic composed of the bitumen and filler fills up all the voids between the grains making up the aggregate skeleton of the SMA mixture. This combination is bound to reduce the compaction resistance.

Based on *CDI* we can conclude that a change in the volume of mastic caused in SMA-MA mixtures a much greater decrease of resistance to compaction as compared to AC AF mixtures. The value of *CDI* dropped from 308.92 to 48.79 (i.e. six times) in SMA-MA mixtures, as compared to fold decrease (from 96.63 to 42.58) obtained for the AC AF mixtures. Poorer aggregate skeleton in AC-type of mixtures is one of the relevant factors. These values indicate also a possibly greater sensitivity to variations in the mixture compositions of SMA mixtures, as compared to AC-type mixtures. The type of bituminous binder has also a strong influence on the compaction behaviour due to different viscosities at different compaction temperatures. *CDI* values were higher in the case of PMB-type mixtures, as illustrated in Fig. 10. Eventually we have a smaller effective amount of binder (anti-friction agent), resulting in a higher viscosity (stiffness) of the mixture and lower susceptibility to the compaction effort. Thus the PMB-type mixtures are less susceptible to compaction, as compared to bituminous mixtures including the same amount of non-modified bitumen.

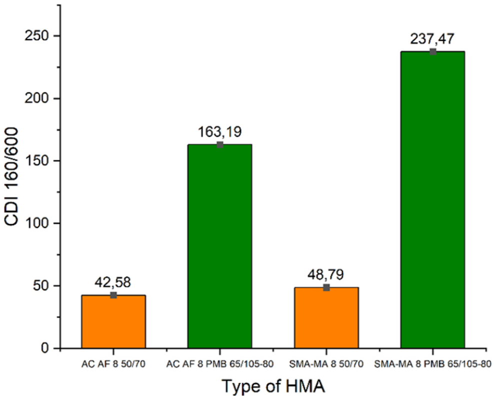

Fig. 10. $CDI_{160/600}$ depending on the binder type

The lowest $CDI_{160/600}$ values were observed in AC AF and SMA-MA mixtures containing 50/70 bitumen, designed for layers to improve cracking (fatigue) resistance. This is because they require a small number of gyrations to achieve the specified compaction in the pre-determined test conditions. This allows us to conclude that AC AF and SMA-MA mixtures, subject to optimum conditions during placement, an achieve the desired compaction after passing the screed with only a minimum compaction effort delivered by rollers. AC AF type mixtures are more sensitive to the compaction conditions which, when unfavourable, may cause problems in achieving the specified density, as evidenced by the increase of $CDI_{130/600}$.

5. Conclusions

The article presents the results of research on the compaction behaviour (compactibility) of AC and SMA-type The specimens were compacted in a gyratory compactor at different temperatures and pressures. The mixtures were assessed based on the final compaction and values of K, CDI, LP. The experimental results and the analyses based on them allow us to draw to the following conclusions:

1. With several indicators that can be used for this purpose (including K, LP, CDI) it is still not possible to assess the compactibility of bituminous mixtures.
2. The tests confirmed the relevance of the temperature and pressure and the strong influence of compaction effort on the achieved physical parameters, specifically the bulk density of the mixture.
3. The standard CDI determination method was modified to assess mixtures with a low content of voids. CDI value was determined between 8-th gyration and the gyration that produced 98% relative compaction.

4. SMA-MA 8 50/70 exhibits the desired compaction characteristics over a wide temperature and pressure range, meaning a longer compaction window during placement, as compared to the other mixtures tested in this research.
5. Considering the K values we should rate the SMA-MA mixtures as superior in terms of compaction behaviour to the AC AF mixtures. However, this indicator should not be used to compare mixtures with different values of $v(1)$ as the method requires, inter alia, similar air voids in the initial phase of compaction. Also assessment of the effect of the bitumen type on the mixture compactibility appears problematic.
6. Locking point is a parameter that depends on the type of bituminous mixture. SMA, SMA-MA and AC S achieve the locking point at higher relative compaction values (above 98%). The exception to that is the AC AF mixture which locks earlier, resulting in a higher resistance to compaction.
7. A higher content of mastic in SMA-MA mixtures, as compared to the conventional SMA mixtures results in a lower resistance to compaction. This applies also to AC AF mixtures, yet to a lesser degree.
8. The type of bituminous binder has a strong influence on the compaction behaviour, related to different viscosities at the compaction temperatures.
9. The values of *CDI* show a substantially greater input of energy required for compaction of PMB based mixtures, as compared to mixtures of the same design, yet containing 50/70 bitumen. This is related to the effective content of PMB binder in the mixtures although the viscosity of the mastic is the primary factor in this respect.

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Analiza zagęszczalności mieszanek mineralno-asfaltowych do warstw przeciwspękaniowych

Słowa kluczowe: mieszanka SMA-MA, prasa żyratorowa, punkt blokowania, zagęszczalność

Streszczenie:

Wbudowanie i zagęszczanie mieszanki mineralno-asfaltowej to etapy kształtujące jej właściwości fizyczno-wytrzymałościowe. Celem zagęszczania jest zmniejszenie zawartości wolnych przestrzeni i osiągnięcie odpowiedniego ułożenia ziaren dla uzyskania warstwy o założonych na etapie projektowania parametrach. Efektywność tego procesu zależy od wkładu pracy zagęszczania i jest ściśle związana z temperaturą mieszanki. W badaniach skupiono się głównie na ocenie zagęszczalności mieszanek do warstw przeciwspękaniowych wbudowywanych najczęściej w cienkich warstwach. Materiałwbudowany w cienkich warstwach (grubościach rzędu 20–30 mm) ma mniejszą pojemność cieplną co skutkuje szybszym jego wychłodzeniem w wyniku oddziaływania czynników zewnętrznych (tj. wiatr, woda, temperatura podłoża) podczas procesu zagęszczania. Dąży się zatem, aby proces zagęszczania prowadzić w temperaturach, w których lepkość dynamiczna lepiszcza asfaltowego mieści się w granicach 2–20 Pa·s. Dla mieszanek cienkowarstwowych oznacza to, że czas na zagęszczanie jest bardzo krótki, a proces musi rozpocząć się bezpośrednio za stołem rozkładarki. Z tego względu istotnym kryterium oceny cienkich warstw na gorąco stosowanych do warstw przeciwspękaniowych jest ich szczelność, urabialność i podatność do wbudowania (zagęszczalność). Aby wykonana warstwa przeciwspękaniowa działała jak membrana odpowiednio odkształcalna, zdolna do absorbowania i rozpraszania naprężeń powinna charakteryzować się jak najniższą zawartością wolnych przestrzeni (ok. 1–2%), dużą zawartością lepiszcza (w ujęciu objętościowym), drobnym uziarnieniem, odpowiednią grubością (ok. 20–30 mm) i bardzo dużą odpornością na zmęczenie i rozciąganie w szerokim zakresie temperatur. Warunki te spełniają drobnoziarniste mieszanki mineralno-asfaltowe na bazie asfaltu wysokomodyfikowanego (polimerami lub miałem gumowym) stosowane dotychczas do warstw przeciwzmęczeniowych. Przykładem może być AC AF (AF – Anti-Fatique), tj. beton asfaltowy do warstw przeciwzmęczeniowych, składający się głównie z kruszywa drobnego (do 5 lub 8 mm), wypełniacza (10–15%) i dużej ilości lepiszcza (8–15%). Niestandardowym materiałem w tego typu rozwiązaniach mogą być również mieszanki mastyksowo-grysowe o zwiększonej zawartości mastyksu SMA-MA, które do tej pory stosowane były głównie jako warstwy ochronne obiektów mostowych. Do badań wybrano mieszanki drobnoziarniste o uziarnieniu do 8 mm i zróżnicowano je ze względu na rodzaj lepiszcza asfaltowego (asfalt drogowy 50/70 oraz asfalt

wysokomodyfikowany PMB 65/105-80). Analizę zagęszczalności przeprowadzono dla mieszanek typu betonowego (AC S, AC AF) i mieszanek mastyksowo-grysowych (SMA i SMA-MA). W ramach prowadzonych badań próbki zagęszczano prasą żyratorową zgodnie z normą PN-EN 12697-31:2019-03 w trzech temperaturach badawczych (100°C, 130°C i 160°C) i przy zróżnicowanym ciśnieniu kontaktowych (150 kPa i 600 kPa). Na podstawie pomiarów prowadzonych w prasie żyratorowej wyznaczono dla każdej z mieszanek przy zmiennych temperaturach i ciśnieniu współczynnik zagęszczalności K, żyratorowy punkt blokowania (LP) oraz wskaźnik CDI. W analizie ogólnej zaobserwowano, że dla mieszanek typu SMA-MA 8 na bazie asfaltu drogowego 50/70 uzyskanie wymaganego wskaźnika zagęszczenia jest możliwe w szerokim zakresie temperatur od 100°C do 160°C. To oznacza, że czas efektywnego zagęszczania na budowie jest dla tej mieszanki dłuższy i jest ona mniej wrażliwa na zmiany temperatury od pozostałych badanych mma. Dodatkowo mieszanka SMA-MA 8 50/70 zagęszcza się również przy obniżonej energii zagęszczania wyrażonej ciśnieniem kontaktowym o wartości $c = 150$ kPa (w stosunku do typowej $c = 600$ kPa). W temperaturze 130°C przy ciśnieniu $c = 600$ kPa mieszanki typu AC AF nie uzyskują wymaganego poziomu zagęszczenia, w przeciwieństwie do mieszanek typu SMA i SMA-MA. Za optymalne warunki zagęszczania dla wszystkich badanych mieszanek można przyjąć $T = 160$°C oraz ciśnienie $c = 600$ kPa. Dla tych parametrów wszystkie badane ma spełniły warunek zagęszczenia (wolnej przestrzeni) odpowiadającego założeniom recepty (BT – Badania Typu). Szczegółowo podatność do zagęszczania mieszanek mineralno-asfaltowych oraz efektywność tego procesu analizowano w oparciu o wskaźnik zagęszczalności K, współczynnik *CD*I oraz *LP*. W oparciu o wartość wskaźnika K można wnioskować, że mieszanki SMA-MA są bardziej podatne na zagęszczenie niż mieszanki AC AF. Jednak ze względu na ograniczenia tej metody nie powinno się jej stosować do porównania mieszanek o różnej wartości wolnych przestrzeni w początkowej fazie zagęszczania. Problematyczna jest również ocena wpływu rodzaju asfaltu na zagęszczalność mieszanki przy wykorzystaniu współczynnika K. Analiza wskaźnika *CDI* pokazała, że do zgęszczenia ma na bazie asfaltów wysokomodyfikowanych (PMB) potrzeba znacznie więcej energii niż w przypadku tych samych mieszanek z asfaltem 50/70. Jest to efektem stopnia modyfikacji lepiszcza i jego parametrów, m.in. wyższej lepkości w zakresie stosowanych temperatur zagęszczania oraz lepkością mastyksu. Punkt blokowania związany jest z typem mieszanki mineralno-asfaltowej. Analiza punktu blokowania (*LP*) pokazała, że mieszanki typu SMA i SMA-MA uzyskują wskaźnik zagęszczenia na poziomie 98% przed pojawieniem się punktu blokowania, czyli momentu, w którym mieszanka stawia wyraźny opór dla dalszego zagęszczania. Odwrotną charakterystykę zauważono w przypadku mieszanek typu AC S i AC AF. Zwiększona zawartość mastyksu w mieszankach SMA-MA w stosunku do tradycyjnych miejszanek SMA powoduje spadek oporu zagęszczania. Podobnie jest w przypadku mieszanek AC AF, ale zmiany są znacznie mniejsze. Podsumowując spośród badanych mieszanek najlepsze predyspozycje do zagęszczania w szerokim zakresie temperatur (100–160°C) i ciśnienia (150 kPa, 600 kPa) wykazuje mieszanka SMA-MA 8 50/70. Projekt innowacyjnej mieszanki SMA-MA zakłada wzrost zawartości wypełniacza oraz lepiszcza asfaltowego w stosunku do typowej mieszanki SMA. Taka kompozycja mieszanki powoduje spadek oporu zagęszczania i mieszanka SMA-MA staje się łatwiej zagęszczalna niż typowa mieszanka SMA.

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