applied sciences

MDPI

Article

Application of Innovative SMA-MA Mixtures on Bridges

Bartosz Budziński * and Paweł Mieczkowski

Faculty of Civil and Environmental Engineering, West Pomeranian University of Technology, 70-310 Szczecin, Poland; Pawel.Mieczkowski@zut.edu.pl

* Correspondence: bbudzinski@zut.edu.pl

Received: 10 September 2020; Accepted: 1 October 2020; Published: 5 October 2020

Abstract: This paper presents a case study of the application of an innovative asphaltic mixture used for making protective layers on bridges. This mixture, called stone mastic asphalt rich in bitumen mastic (shortened to SMA-MA) produces an impervious surface, resistant to permanent deformation and fatigue, easily produced and laid down on bridge decks. The authors analyzed the state of knowledge on the asphalt mixtures used on bridges. This article describes the first trials with the SMA-MA mixtures and an example of the most spectacular application.

Keywords: bridge pavement; protective layer; modified bitumen

1. Conventional Asphalt Pavements Used on Bridges

Bridge pavements behave differently from typical pavements placed on the ground. There are a number of design criteria that can be used to design road pavements with optimum dimensions [1–3] yet these criteria are not applicable to bridge pavements. In the latter case, there are no unequivocal design criteria [4,5] and conventional design methods turn out to be inadequate for bridge pavements [6]. The actual life of bridge pavements turns out to be shorter [7] than the life of ground-supported pavements. In addition, bridge designers, focusing primarily on the structural aspects and the load capacity of the bridge itself, fail to approach the problem of bridge pavement durability in a correct manner. On bridges we deal with specific loading conditions [8,9], different from those found in the case of ground-supported structures. These specific conditions include, without limitation, the possibility of high amplitudes of vertical deflections (imposed by vehicles) and horizontal displacements (due to temperature variation) and vibration of the supporting structure. Bridge pavements have the following main functions [10,11]:

- Spread the loads over the bridge deck;
- Dampen the dynamic effects caused by traffic loading;
- Accommodate strains of the bridge deck caused by temperature variation in the range −30 °C to +70 °C;
- Ensure the required interlayer bond, including bond between the waterproofing layers and the deck;
- Ensure the required evenness, tightness, surface roughness and resistance to abrasion, rheological effects and rutting;
- Reduce sensitivity of the asphalt mixtures to both low and high temperatures.

Different designs were applied in Poland and other European countries for bridge pavements [12,13]. At present, bitumen-bound materials [4,9,13,14] are used most often on bridges. The conventional surfacing systems used on bridge decks comprise the waterproofing layer, protective (binder) course and wearing course (Figure 1).

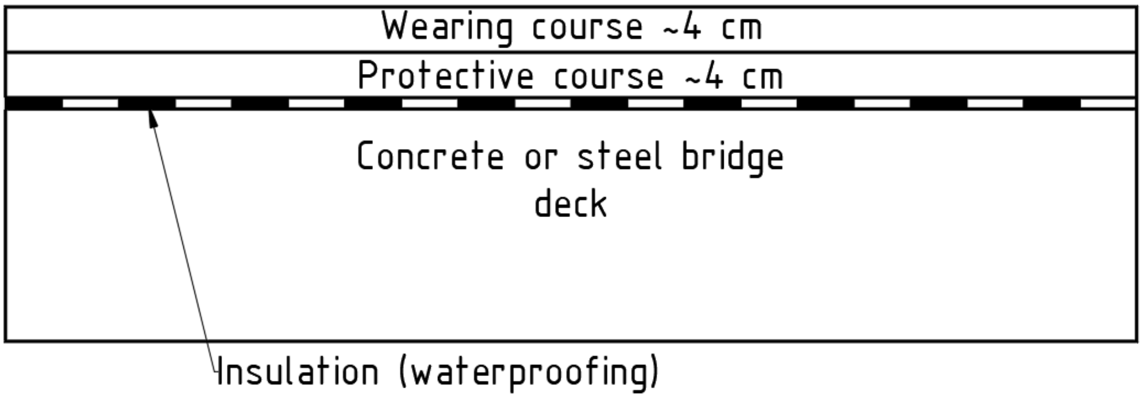

Figure 1. Typical arrangement of pavement layers on the bridge deck.

The waterproofing layer is an important part of the bridge surfacing system and should [15–17]:

- Be impervious to water, water vapor and gases;
- Be resistant to the action of chemicals related to operation and maintenance of roads;
- Have smooth surface to facilitate drainage of water from the surface and reinforcing fleece embedded in the binder (if designed);
- Be made of materials whose coefficient of thermal expansion is similar to that of the bridge deck,
- Be elastic over a wide temperature range (–30 °C to +70 °C);
- Adhere well to base and ensure good bond with the protective or wearing courses (in the case of one-layer surfacing systems);
- Be resistant to mechanical damage and the working temperatures of asphalt mixture used for the protective layer (at least 160–240 °C).

The waterproofing layer should be at least 5 mm thick in the case of sheet materials and at least 2 mm thick in the case of coatings.

Torch-on membranes are the most popular deck waterproofing material used on the bridges in Poland [18]. However, torch-on membranes involve certain risks, related, inter alia to their application (bonding to the base in particular) and the process of placing of mastic asphalt to the protective course. These risks include [19–21]:

- Burning through the membrane during application (the temperature of burned gasses during heating up the underside of the membrane with a gas torch can reach from about 700 °C to as much as 1400 °C) (Figure 2).

Figure 2. Application of a torch-on membrane—heating up the material with gas torches.

- Forming of bulges during placement of the protective layer due to local lack of adhesion between the membrane and substrate and the increase in partial pressure of air in the voids.
- Destruction of membrane (structural degradation).

Spray applied polymer based compounds, such as methyl methacrylate, are increasingly used for the waterproofing of bridge decks.

The wearing course on bridges (in accordance with WT-2:2014 [22] manual) is most often made of asphalt concrete (AC), mastic asphalt (MA), stone mastic asphalt (SMA) and asphalt mixtures of discontinuous grading (BBTM). The requirements for these courses are the same as for the pavement structure outside the bridge.

In the Polish design manuals [22] mastic asphalt MA is the only material allowed for placement of protective layers. Mastic asphalt is widely used worldwide [23,24]. These mixtures were developed at the beginning of the 20th century almost simultaneously in England and France [25]. In Europe, MA mixtures are designed on the basis of the standard EN 13108-6 [26]. The strength parameters of these mixtures depend primarily on a very high viscosity (cohesion) of the mastic part (mixture of the bituminous binder, filler and fine sand). Hard penetration grade bitumens (20/30, 35/50) featuring low penetration and high viscosity (cohesion) are often used in order to increase cohesion of the bitumen mastic in the service temperature range. The disadvantage of this option is that mastic asphalt can be prone to low-temperature cracking. For this reason, for over a dozen years polymer-modified bitumens have been increasingly used for production of mastic asphalts, owing to their higher resistance to this phenomenon (soft base bitumens). On the other hand, asphalts of this kind are sensitive to high temperatures (over 180–190 °C) due to the risk of polymer degradation [23]. For this reason, viscosity-reducing additives are added to polymer-modified bitumens (such as FT waxes, Montana waxes, etc.) [27].

Besides undisputable advantages (self-compaction, tightness, long service life), mastic asphalt mixtures also have some disadvantages, including the following [28–32]:

- Special pavers and vehicles are needed, which due to a relatively low availability and low throughput of this kind of plant considerably extends the process of construction, in relation to the projects where conventional asphalt mixtures are used;
- High temperatures during production of mastic asphalt have a negative impact on the natural environment and increase the risk of overheating the bitumen;
- Use of a layer of mastic asphalt may lead to cracking (longitudinal and transverse) and de-bonding of layers as a result of shrinkage, especially when there are considerable temperature differences of ambient air and longitudinal joint construction is applied because full-width working is not possible (Figures 3 and 4);
- It is not possible to check the composition of MA mixtures immediately after production due to, inter alia, a lack of filler heating systems in asphalt mixing plants.

Figure 3. Longitudinal joints in a mastic asphalt pavement constructed in stages [33].

Figure 4. Distressed wearing course due to shrinkage and cracking of the protective layer of mastic asphalt.

The high temperature during placement of mastic asphalt increases the risk of blistering [34] on the placed layer due to the rise of pressure in the voids and poor adhesion between the base and the torch-on membrane waterproofing layer [35,36]. The primary effect of the high temperature is the increase in water vapor pressure and, to a small extent, also the dry air pressure. Large increases in water vapor pressure are noticeable above 100 °C [28] (Figure 5).

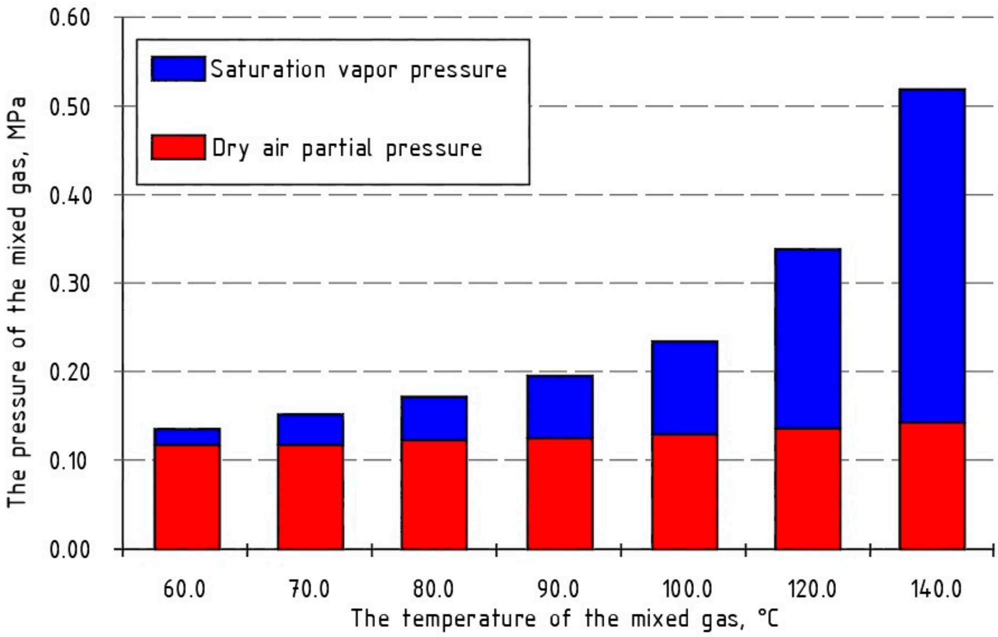

Figure 5. The effect of temperature on the saturation vapor pressure and dry air partial pressure.

2. Innovative SMA-MA Mixtures—Brief History, General Information

In the 1990s, a research project was conducted at the Szczecin University of Technology concerning the application of a new mixture, which was expected to ensure functionality and durability of pavements used on bridges [37]. Concepts of stone mastic asphalt with an increased amount of bituminous binder and filler (SMA-MA) date back to that time [38]. These mixtures should be treated as a development of the German technology developed in 1960s/1970s. Stosch [39] proposed five typical pavement structures designed for bridges with a steel plate deck. For the protective layer, which simultaneously functioned as the waterproofing layer, Stosch proposed, inter alia, a layer of asphalt mastic laid on a special bonding coat, protecting the deck plate from corrosion (Figure 6).

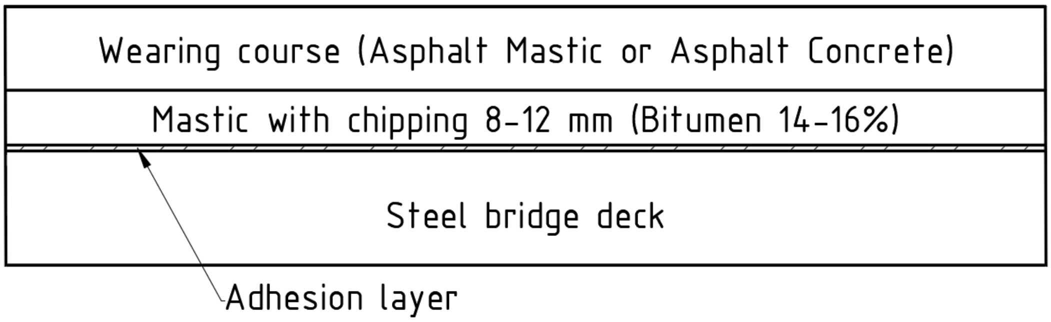

Figure 6. Pavement with a bitumen mastic layer laid on the bonding coat according to Stosch.

Bitumen mastic designed for waterproofing applications is composed of about 14–16% of bituminous binder, filler and sand. It features very good waterproofing properties but lacks resistance to permanent deformations. For this reason, 8/12 mm chippings were added to increase resistance to viscoplastic deformations caused by vehicle wheels.

The level of vehicle loading on pavements has considerably increased. As a result, the design used in the 1960s/1970s can lead to permanent deformations, most undesirable in the case of bridges, taking into account safety and major traffic disturbance during repair works. SMA-MA mixtures can provide a satisfactory solution to this problem. The main technical advantages of innovative SMA-MA mixtures include, but are not limited to, the following [38,40]:

- Placement by conventional asphalt pavers;
- The range of working temperatures does not depart much from the temperatures typically used in the case of asphalt concrete or SMA mixtures (lower by 40–60 °C than the temperatures used for mastic asphalts);
- Lower risk of overheating the binder during lay-down;
- High tightness of the layer;
- Fatigue resistance owing to an increased content of medium penetration bitumen (mainly modified).

SMA-MA mixtures combine the advantages of bitumen mastic, mastic asphalt and SMA mixtures. In this way, we obtain a watertight and elastic material, which, in addition features a resistance to permanent deformations [38,41] and has good rheological parameters, especially at low temperatures [42]. Mixtures of this kind, owing to a large proportion of chippings, enable introduction to the binder (and thus to its mixture with aggregate) of larger amounts of polymer. A larger amount of polymer improves the elastic properties of the layer, reducing the effect of tensile and shear stresses caused by the temperature variation and traffic [37]. The recommended thickness of layers ranges from 1.5 to 3.5 cm (4.0 cm is acceptable) with the recommended grading of 5 mm or 8 mm (in exceptional situations grading of up to 11 mm is acceptable).

In Poland, SMA-MA mixtures have been, so far, used primarily in the West Pomerania province [28]. Attempts were also made to apply this technology on the Grota Roweckiego bridge in Warsaw but the project was discontinued due to the concerns of the Building Control Office [43]. One of the first successful implementations was the renewal of the Cłowy bridge in Szczecin in 1998 [37,44]. Instead of the conventional torch-on membrane, a spray-applied 2–3-mm-thick layer of paving-grade bitumen was applied as the bridge deck waterproofing. It was protected with a SMA mixture with an increased content of 50/70 paving-grade bitumen and low void content (about 0.5%). The layer was 2 cm thick (Figure 7). The mixture contained about 70% of chippings. Bitumen in the mixture was modified with carboxylated styrene butadiene latex which had stabilizing effect, i.e., reduced drainage of binder from the aggregate particles. The SMA layer was compacted until binder appeared on the surface. Upon placement, the SMA layer provided protection to the bituminous coating (with bonding and waterproofing functions). Due to relatively large irregularities of the deck slab and the need to obtain adequate transverse profile a regulating course was placed, made of asphalt concrete mixture containing max. 12.8 mm aggregate. The surfacing (wearing course) was a 4-cm-thick asphalt concrete layer (also with max. 12.8 mm aggregate). The total thickness of all the pavement courses was 10 cm. This pavement was successfully used until 2017 when the bridge was taken down due to a failure of a span (due to damaged deck pre-stressing elements).

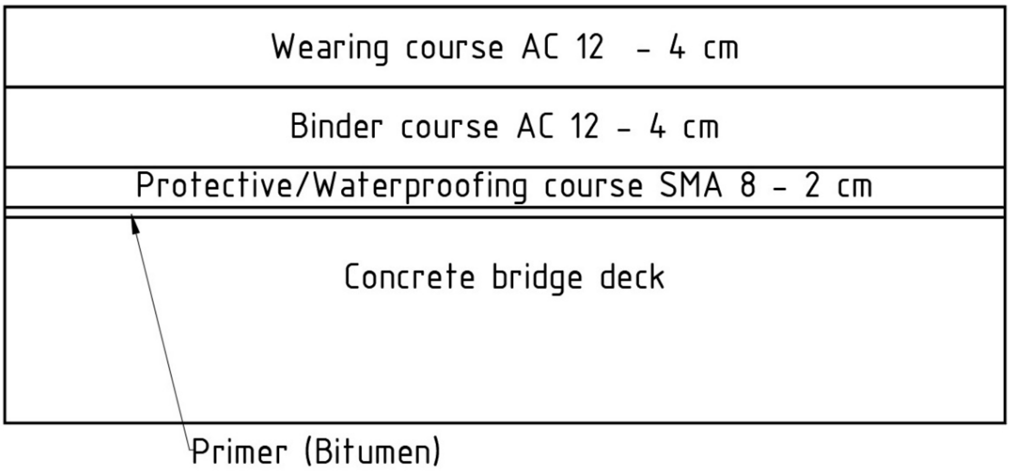

Figure 7. Structure of pavement on the Cłowy Bridge in Szczecin (constructed in 1998).

The SMA-MA mixture has also been used in other projects, including: Długi bridge in Szczecin (completed in 2000), Akademicki overpass in Szczecin (completed in 2001), road overpass in Police (completed in 2013), road bridge over S3 expressway (interchange Tczewska – completed in 2014), and the bridge over Dzierżęcinka river in Koszalin (2014). Examples of the application of the SMA-MA mixture are displayed in Figures 8–10 below.

Figure 8. Current condition of pavement with the protective layer made of stone mastic asphalt (SMA) 5 mixture with increased content of bitumen mastic on the overpass supporting Mickiewicza St. in Szczecin (year of completion: 2001).

Figure 9. Condition of pavement with the protective layer made of SMA 11 mixture with increased amount of bitumen mastic on the overpass supporting Mickiewicza St. in Szczecin in year 2017 (year of completion: 2001).

Figure 10. Current condition of pavement with the protective layer made of stone mastic asphalt rich in bitumen mastic (SMA-MA) 11 mixture on the overpass in Police after 5 years of operation.

3. Use of SMA-MA Mixture—Case Study

3.1. Bridge Description

One of the bigger projects completed in the recent years in which SMA-MA mixture was used was the renewal of the Trasa Zamkowa arterial thoroughfare linking the parts of Szczecin divided by the Odra river. In the period of 2017–2018 the city-bound road underwent a comprehensive renewal. This city-bound road runs over two river bridges over the Odra and the Parnica and an overpass over

Łasztownia island [45] (Figure 11). Renewal of the asphalt pavement was one of the elements of the project. Constructed in 1987, after 30 years of operation the pavement was in a very bad condition and required a comprehensive renewal. The original structure of pavement comprised one layer of typical bitumen mastic and two layers of asphalt concrete mixture with 11 mm max. aggregate size. SMA-MA mixture was chosen as the best option upon considering the scope of work and a lack of possibility to close the road to traffic for a longer period of time. The scope of the asphalt paving work comprised construction of pavement with 3–4 travel lanes over a 1818-m-long section of the road.

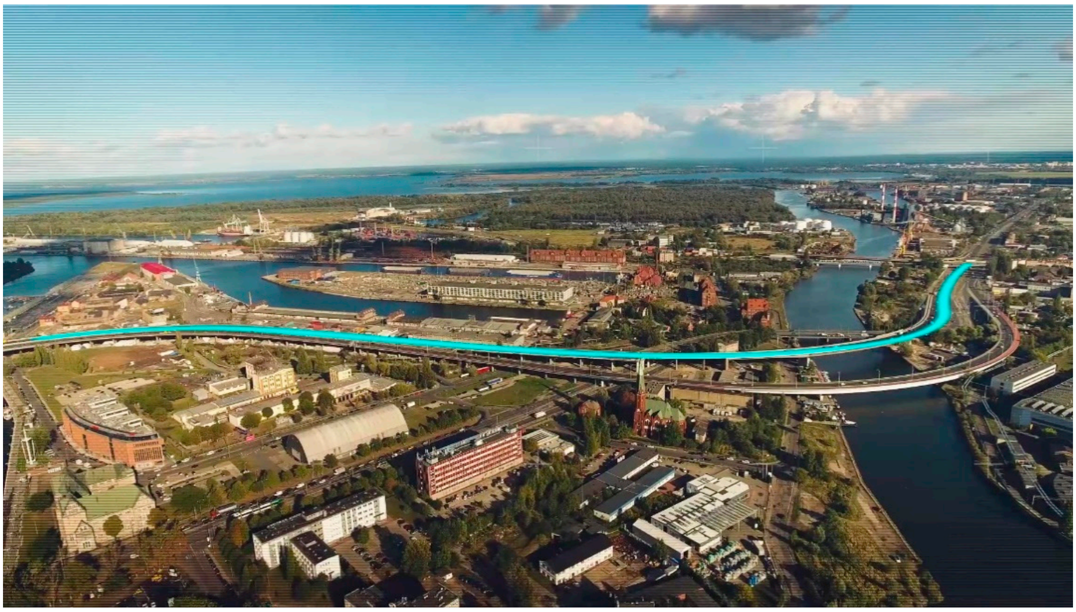

Figure 11. View on a part of the Trasa Zamkowa arterial thoroughfare—city bound road.

The designed pavement is composed of three bituminous layers laid down on a waterproofing layer of liquid methyl methacrylate resin, spray applied on a prepared base (Figures 12 and 13). The waterproofing layer is protected with a about 2.5–3.0 cm thick layer of SMA-MA 8 mixture. The bridge deck gradeline was regulated with a 3.0-cm to 6.0-cm-thick layer of AC 11 S Polymer Modified Bitumen (PMB) 45/80-65 asphalt concrete mixture for wearing course. The wearing course of this pavement was made of a standard SMA 11 PMB 45/80-65 stone mastic asphalt mixture. The wearing course was 4 cm thick.

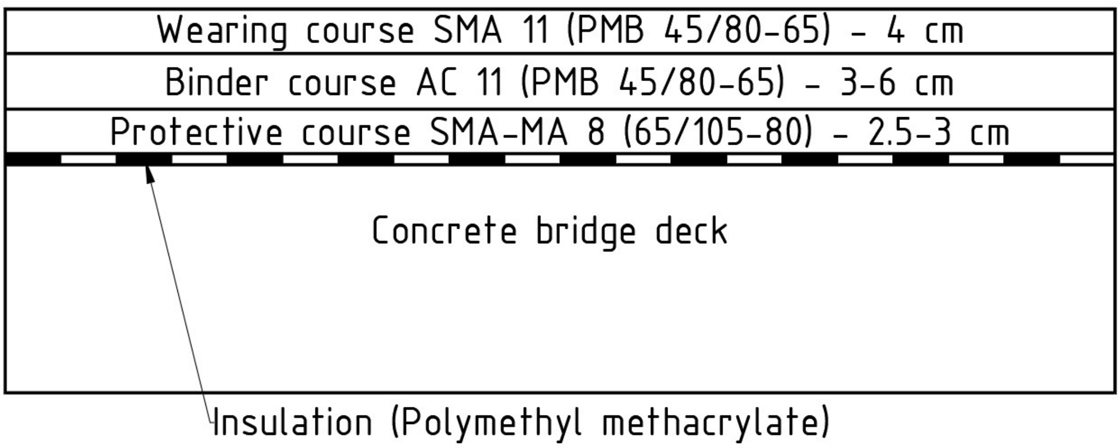

Figure 12. Pavement structure on the Trasa Zamkowa bridge.

Figure 13. Methyl methacrylate waterproofing layer on the Trasa Zamkowa bridge and SMA-MA 8 layer.

3.2. SMA-MA Protective Layer

The protective layer was made of SMA-MA 8 mixture. The binder for the protective layer made of SMA-MA 8 mixture was chosen based on the properties of the bitumen and the mixture in which it was used, including low-temperature performance in particular. Three bitumens were considered: 50/70 paving grade bitumen and two medium modified bitumens, i.e.,: PMB 45/80-65 and PMB 65/105-60. The tested parameters of the bitumens included softening point, penetration at 5 °C and 25 °C, critical temperatures and stiffness modulus obtained from the BBR (Bending Beam Rheometer) test and elastic recovery. The low-temperature properties in the BBR test were determined on specimens aged according to Rolling Thin Film Oven Test (RTFOT) (EN 1267-1) and Pressure Aging Vessel (PAV) (EN 14769) at the following temperatures: −10, −16, −22 and −28 °C. The samples were subjected to a constant, controlled temperature for 60 min. and the values were read after 60 sec. of load application. The following parameters were determined in the tests:

- Critical temperature ($T(S)_{60}$) at 300 MPa creep stiffness;
- Critical temperature at the value of m ($T(m)_{60}$) equal to 0.3;
- Stiffness of bitumen at the temperature of −16 °C ($S(T)_{-16}$).

The obtained properties of bitumens are compiled in Table 1.

The Penetration index *Ip* was calculated from Equation (1), on the basis of the penetration values at 5 °C and 25 °C.

$$I_p = \frac{20 - 500A}{1 + 50A} \quad (1)$$

$$A = \frac{LogP(25°C) - LogP(5°C)}{20} \quad (2)$$

Table 1. Properties of 50/70 paving grade bitumen and two modified bitumens: PMB 45/80-65 and PMB 65/105-60.

Type of Test		Standard	Result		
			50/70	PMB 45/80-65	PMB 65/105-60
Penetration (P) (100 g, 5 s) (× 0.1 mm)	25 °C	EN 1426:2015-08 [46]	62.1	63.2	74.0
	5 °C		10.5	11.5	14.3
Softening point ($T_{R\&B}$) (5 °C/min) [°C]		EN 1427:2015-08 [47]	50.2	75.6	70.8
BBR bending beam test (−10, −16, −22, −28 °C)	$T(S)_{60}$ [°C]	EN 14,771 [48]	−16.6	−18.6	−20.8
	$T(m)_{60}$ [°C]		−15.7	−15.1	−21.1
	$S(T)_{-16}$ [MPa]		302	241	181
Elastic recovery (10 °C) [%]		EN 13,398 [49]	13	93	92
Penetration index (I_p) [−]		EN 12591:2010 (Annex A) [50]	0.24	0.53	0.77

The results from the tests of bituminous binders show that polymer-modified bitumens will be more appropriate for the production of SMA-MA mixtures. Based on the values of low-temperature stiffness S(T)-16, cracking resistance T(S)60 and stress relaxation ability T(m)60 polymer-modified bitumen PMB 65/105-60 was chosen. The elastic properties of both these modified bitumens and their rheological type are at a similar level. The parameters of 50/70 unmodified bitumen are worse, in particular in terms of low-temperature cracking.

In the case of SMA-MA the choice of bitumen was also connected with the cracking resistance determined with the Thermal Stress Restrained Specimen Test (TSRST) according to EN 12697-46 [51]. The equivalent failure temperatures of the tested mixtures are compiled in Table 2.

Table 2. Determination of low temperature resistance of MA-MA 8 mixture in the Thermal Stress Restrained Specimen Test (TSRST).

Property	SMA-MA 8 50/70	SMA-MA 8 45/80-65	SMA-MA 8 65/105-60
Failure Temperature $T_{failure}$ (°C)	−28.5	−34.8	−36.3
Failure Stress $\sigma_{cry,failure}$ (MPa)	3.2	5.0	5.2

PMB 65/105-60 (according to [52]) was the binder finally chosen for the production of the SMA-MA mixture, added at a rate of 9.1% (m/m). The gradation curve of aggregate in SMA-MA 8 mixture is displayed in Figure 14 below.

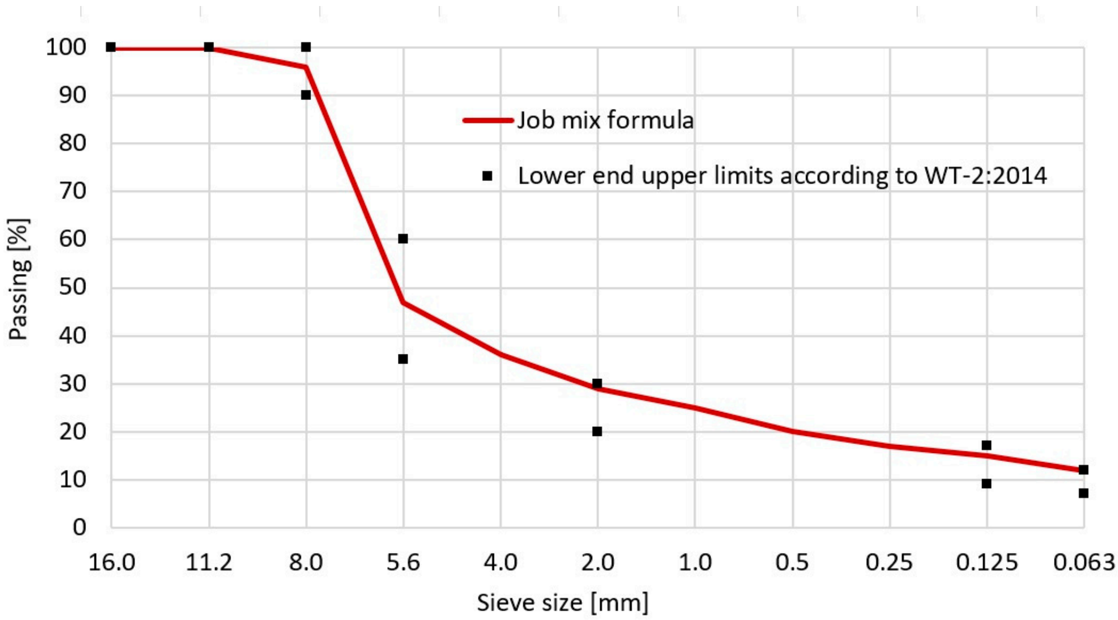

Figure 14. Gradation curve of SMA-MA 8 mixture.

The requirements for SMA-MA 8 PMB 65/105-60 mixture are given in Table 3 below.

Table 3. Properties of SMA-MA 8 PMB 65/105-60 continuously graded mixture for protective layer and KR3-7 traffic service level.

Property	Compaction according to EN 13108-20	Test Method	Requirements according to TS [(1)]	Value
Air Void Content, V (%)	C.1.1, impact compaction, 2 × 25 blows, EN 12697-30 [53]	EN 12697-8 [54]	$V_{max1.5}$	1.3
Air Void Content, V (%)	C.1.2, impact compaction, 2 × 50 blows, EN 12697-30 [53]	EN 12697-8 [54]	$V_{max1.0}$	0.7
Resistance to permanent deformation of the protective layer (SMA-MA) WTS_{AIR} (mm/10^3 cycles) PRD_{AIR} (%)	C.1.20, slab compactor, P_{98}-P_{100}, EN 12697-33 [55]	EN 12697-22 [56], EN 13108-20 [57], D.1.4 [(2)]	$WTS_{AIRmax0,50}$ $PRD_{AIRmax16.0}$	0.10 13.2
Resistance to permanent deformation of the layer package (protective and wearing courses) WTS_{AIR} (mm/10^3 cycles) PRD_{AIR} (%)	C.1.20, slab compactor, P_{98}-P_{100}, EN 12697-33 [55]	EN 12697-22 [56], EN 13108-20 [57], D.1.5 [(3)]	$WTS_{AIRmax0,15}$ $PRD_{AIRmax9.0}$	0.09 8.1
Water sensitivity (%)	C.1.1, impact compaction, 2 × 35 blows, EN 12697-30 [53]	EN 12697-12 [(4)] [58]	$ITSR_{min90}$	98
Binder drainage (%)	–	EN 12697-18 [59]	$BD_{max0.6}$	0.5

(1) TS—technical specifications. (2) Small device, procedure B, medium—air, 45 °C, 10,000 cycles. (3) Small device, procedure B, medium—air, 50 °C, 10,000 cycles. (4) Sample conditioning temperature—40 °C, one freezing cycle, test temperature –25 °C.

3.3. Pavement Lay-Down Process

The SMA-MA 8 protective layer was laid down by conventional asphalt pavers. The works were carried out in stages (lane by lane) to avoid road closure. The placed layer was compacted by steel rollers until bitumen mastic appeared on the surface (Figures 15 and 16).

Figure 15. Compaction of the SMA-MA 8 PMB 45/80-65 protective layer.

Figure 16. Surface of the SMA-MA layer after compaction.

The placement of the AC 11 S protective course and SMA 11 wearing course is displayed in Figures 17 and 18.

Figure 17. Compaction of binder course of asphalt concrete (AC) 11 S PMB 45/80-65 mixture.

Figure 18. Placement of wearing course of SMA 11 PMB 45/80-65 mixture.

The condition of pavement on the Trasa Zamkowa bridge two years after renewal is presented in Figure 19.

Figure 19. Bridge pavement with the protective layer made of SMA-MA 8 mixture two years after renewal.

4. Conclusions

Contemporary, sustainable construction calls for new, optimized materials and technologies. The SMA-MA mixture used for installation of protective courses on bridges is an example of such materials. Based on the experiences with the SMA-MA mixture, we can derive the following conclusions:

1. After over 20 years from the first implementations we can state that SMA-MA mixtures feature the required durability and load capacity;
2. The construction joints (hot-to-cold) after placement of SMA-MA mixture ensure tightness and uniformity of the surface (without the need of additional sealing), thus enabling staged, lane-by-lane construction;
3. SMA-MA mixtures are produced in standard batching plants at much lower (i.e., by 40–60 °C) temperatures as compared to MA mixtures, thus reducing the carbon footprint and increasing the throughput;
4. SMA-MA can be laid down by typical hot mix asphalt pavers, which considerably reduces the construction time (as compared to MA mixtures);
5. The SMA-MA protective course in combination with spray applied liquid resin waterproofing systems, such as methyl methacrylate products, enables reducing the negative effect of the increase in pressure in the air voids under the torch-on membrane layer;
6. Polymer-modified bitumen gives the mixture high fatigue resistance and good low-temperature performance, which is of particular importance on steel bridges.

Author Contributions: Conceptualization, B.B.; methodology, P.M and B.B..; investigation, P.M.; Formal Analysis, P.M. and B.B; writing—original draft preparation, B.B.; writing—review and editing, P.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Judycki, J.; Jaskuła, P.; Pszczoła, M.; Ryś, D.; Jaczewski, M.; Alenowicz, J.; Dołżycki, B.; Stiness, M. *Analizy i Projektowanie Konstrukcji Nawierzchni Podatnych i Półsztywnych*; WKŁ: Warszawa, Poland, 2014; ISBN 978-83-206-1928-7.
2. Ara, Inc. *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures, Final Report, Part 3–Design and Analysis*; NCHRP, TRB, NRC: Champaign, Illinois, 2004.
3. Ministere de l'Equipement, des Transports et du Tourism. *French Design Manual for Pavement Structures, Guide Technique*; LCPC, SETRA: Paris, France, 1997.
4. Radziszewski, P.; Piłat, J.; Sarnowski, M.; Kowalski, K.; Pokorski, P.; Liphardt, A. *Rozwiązania Materiałowo-Technologiczne Izolacji i Nawierzchni Obiektów Mostowych*; Raport Końcowy; GDDKiA: Warsaw, Poland, 2013.
5. Caliendo, C. Simplified models for estimating stresses and strains in pavements on concrete and steel bridges. *IJCIET* **2017**, *8*, 1273–1282.
6. Castro, M. Structural design of asphalt pavement on concrete bridges. *Can. J. Civ. Eng.* **2004**, *31*, 695–702. [CrossRef]
7. Piłat, J.; Radziszewski, P.; Kowalski, K. Jaka nawierzchnia, taki most. *Nowocz. Bud. Inżynieryjne* **2007**, *3*, 4.
8. Madaj, A.; Wołowicki, W. *Budowa i Utrzymanie Mostów*; WKŁ: Warszawa, Poland, 2009; ISBN 978-83-206-1848-8.
9. Sybilski, D. Bitumiczne nawierzchnie mostowe. *Drogownictwo* **1994**, *7*, 232–238.
10. Rozporządzenie ministra Transportu i Gospodarki Morskiej w sprawie warunków technicznych, jakim powinny odpowiadać drogowe obiekty inżynierskie i ich usytuowanie. *Dz.U.* **2000**, *63*, 735.
11. Wegan, V. *Surfacing of Concrete Bridges*; Report No. 106; Danish Road Institute: Roskilde, Denmark, 2000; ISBN 87-90145-71-2.

12. Głomb, J. Tendencje rozwojowe w projektowaniu nawierzchni mostów drogowych. *Drogownictwo* **1972**, 86–92.
13. Śliwiński, J.; Furtak, K. *Materiały Budowlane w Mostownictwie*; WKŁ: Warszawa, Poland, 2004; ISBN 978-83-206-1531-9.
14. Piłat, J.; Radziszewski, P. *Nawierzchnie Asfaltowe*; WKŁ: Warszawa, Poland, 2007; ISBN 978-83-206-1759-7.
15. Kilarski, A. *Analiza i Ocena Materiałów Hydroizolacyjnych na Pomosty Obiektów Mostowych*; IBDiM: Warsaw, Poland, 1996.
16. Piłat, J.; Radziszewski, P. Izolacje przeciwwodne obiektów mostowych. *Materiały Budowlane* **2003**, *4*, 72–73.
17. Germaniuk, K.; Kilarski, R.; Łukowski, P.; Michalowska, M.; Pryga, A.; Wysokowski, A.; Żurawicka, A. *Katalog Zabezpieczeń Powierzchniowych Drogowych Obiektów Inżynierskich*; Instytut Badawczy Dróg i Mostów: Warsaw, Poland, 2002.
18. Radziszewski, P.; Piłat, J.; Sarnowski, M.; Kowalski, K.; Król, K.J. *Nawierzchnie Asfaltowe na Obiektach Mostowych*; Oficyna Wydawnicza Politechniki Warszawskiej: Warszawa, Poland, 2016.
19. Mieczkowski, P. Nowe papy termozgrzewalne - układy wentylowane. *Izolacje* **2010**, *15*, 36–42.
20. Danowski, M. Doświadczenia z izolacjami i nawierzchniami na obiektach mostowych. *Nowości Zagranicznej Techniki Drogowej* **2000**, *141*, 85–104.
21. Radziszewski, P.; Piłat, J.; Sarnowski, M. Influence of high temperature on properties of materials used in bridge asphalt pavement structures. *Roads Bridges Drogi Mosty* **2015**, 175–191. [CrossRef]
22. WT-2 2014—część I Mieszanki mineralno-asfaltowe. In *Wymagania Techniczne*; Generalna Dyrekcja Dróg Krajowych i Autostrad: Warsaw, Poland, 2014.
23. Zou, G.; Xu, X.; Li, J.; Yu, H.; Wang, C.; Sun, J. The Effects of Bituminous Binder on the Performance of Gussasphalt Concrete for Bridge Deck Pavement. *Materials* **2020**, *13*, 364. [CrossRef] [PubMed]
24. Luo, S.; Qian, Z.; Yang, X.; Wang, H. Design of gussasphalt mixtures based on performance of gussasphalt binders, mastics and mixtures. *Constr. Build. Mater.* **2017**, *156*, 131–141. [CrossRef]
25. Nikolaidēs, A. *Highway Engineering: Pavements, Materials and Control of Quality*; CRC Press: Boca Raton, FL, USA, 2017; ISBN 978-1-138-89376-4.
26. *EN 13108-6:2016-07 Bituminous Mixtures—Material Specifications—Part 6, Mastic Asphalt*; CEN: Brussels, Belgium, 2016.
27. Mazumder, M.; Kim, H.; Lee, S.-J. Performance properties of polymer modified asphalt binders containing wax additives. *Int. J. Pavement Res. Tech.* **2016**, *9*, 128–139. [CrossRef]
28. Budziński, B.; Mieczkowski, P.; Sarnowski, M. *Doświadczenia w Zastosowaniu Technologii SMA-MA*; Krakowskie Dni Nawierzchni: Kraków, Poland, 2016.
29. Mieczkowski, P. Warstwy ochronne z mieszanek mineralno-asfaltowych na obiektach mostowych Izolacje. *Izolacje* **2012**, *10*, 54–61.
30. Mieczkowski, P. Alternatywne systemy izolacji płyt obiektów mostowych. *Mag. Autostrady* **2014**, *10*, 30–34.
31. Mieczkowski, P. Hydroizolacja płyt pomostów na obiektach mostowych. *Bud. Most. Vadem.* **2015**, 11–17.
32. Giu-Lian, Z.; Xiao-Ning, Z.; Chung, W. Evaluation of Steel Bridge Deck Ma Mixture Properties during Construction. *J. Mar. Sci. Technol.* **2015**, *23*, 293–301. [CrossRef]
33. Bichajło, L.; Siwowski, T. Nawierzchnie na obiektach mostowych—doświadczenia z nadzoru nad realizacją. Sympozjum: Nawierzchnie i izolacje na obiektach inżynieryjnych betonowych i stalowych. Konsekwencje i możliwości działań. In Proceedings of the XVII Międzynarodowe Targi Budownictwa Drogowego AUTOSTRADA-POLSKA, Kielce, Poland, 11–12 May 2011.
34. Hailesilassie, B.; Partl, M. Mechanisms of asphalt blistering on concrete bridges. *J. ASTM Int.* **2012**, *9*, 1–16. [CrossRef]
35. Rosenberg, J. *Thin Pavements with Synthetic Binder Used in Denmark, Report No. 105*; Danish Road Institute: Roskilde, Denmark, 2001; ISBN 978-87-90145-73-6.
36. Hailesilassie, B.W.; Partl, M.N. Adhesive blister propagation under an orthotropic bituminous waterproofing membrane. *Constr. Build. Mater.* **2013**, *48*, 1171–1178. [CrossRef]
37. Mieczkowski, P. Mastyks grysowy (SMA) jako warstwa izolacyjna pod nawierzchnie bitumiczne na obiektach inżynierskich. In *Splittmastix as an Insulation for Roads' Pavements on an Engineering Objects*; IBDiM: Kielce, Poland, 2000; pp. 155–161.

38. Radziszewski, P.; Sarnowski, M.; Piłat, J.; Mieczkowski, P.; Król, K.J. Innovative SMA-MA Mixture for Bridge Asphalt Pavement. In Proceedings of the 6th Eurasphalt & Eurobitume Congress, Prague, Czech Republic, 1–3 June 2016.
39. Stosh, H.J. *Błędy Wykonawstwa Nawierzchni Bitumicznych*; WKŁ: Warszawa, Poland, 1977.
40. Sarnowski, M.; Radziszewski, P.; Piłat, J.; Kowalski, K.J.; Król, J.B. Ocena trwałości mieszanek mineralno-asfaltowych stosowanych do izolacji i nawierzchni obiektów mostowych. *Bud. Archit.* **2014**, *13*, 233–241. [CrossRef]
41. Pokorski, P.; Radziszewski, P.; Sarnowski, M. Odporność na deformacje trwałe asfaltowych nawierzchni mostowych. *ZNPRzBiS* **2016**, *63*, 429–436. [CrossRef]
42. Pokorski, P.; Radziszewski, P.; Sarnowski, M. Rheological Properties of Asphalt Mixtures for Bridge Pavements. *Procedia Eng.* **2015**, *111*, 637–644. [CrossRef]
43. Gałecki, M.; Kasprzak, A.; Berger, A.; Nadolny, A. Aspekty wykonawcze przebudowy mostu gen. Grota-Roweckiego w Warszawie. *Arch. Inst. Inżynierii Lądowej Politech. Poznańska* **2015**, *19*, 57–73.
44. Mieczkowski, P. Izolacje z pap asfaltowych na mostach. *Izolacje* **2010**, *2*, 16–18.
45. Hołowaty, J. *Multi-Span Bridge Crossing for Improved Road Access to Szczecin Sea Port*; CRC Press: Porto, Portugal, 2015.
46. PN-EN 1426:2015-08. Determination of needle penetration. In *Bitumen and Bituminous Binders*; PKN: Warsaw, Poland, 2015.
47. EN 1427:2015-08. Determination of the softening point - Ring and Ball method. In *Bitumen and Bituminous Binders*; PKN: Warsaw, Poland, 2015.
48. PN-EN 14771:2012. Determination of the flexural creep stiffness—Bending Beam Rheometer (BBR). In *Bitumen and Bituminous Binders*; PKN: Warsaw, Poland, 2012.
49. PN-EN 13398:2017-12. Determination of the elastic recovery of modified bitumen. In *Bitumen and Bituminous Binders*; PKN: Warsaw, Poland, 2017.
50. PN-EN 12591:2010. Specifications for paving grade bitumens. In *Bitumen and Bituminous Binders*; PKN: Warsaw, Poland, 2010.
51. PN-EN 12697-46:2012. *Bituminous Mixtures—Test Methods for Hot Mix Asphalt—Part 46: Low Temperature Cracking and Properties by Uniaxial Tension Tests*; PKN: Warsaw, Poland, 2020.
52. PN-EN 14023:2011. Specification framework for polymer modified bitumens. In *Bitumen and Bituminous Binders*; PKN: Warsaw, Poland, 2011.
53. PN-EN 12697-30:2012. *Bituminous Mixtures—Test Methods for Hot Mix Asphalt—Part 30: Specimen Preparation by Impact Compactor*; PKN: Warsaw, Poland, 2012.
54. PN-EN 12697-8:2005. *Bituminous Mixtures—Test Methods for Hot Mix Asphalt—Part 8: Determination of Void Characteristics of Bituminous Specimens*; PKN: Warsaw, Poland, 2005.
55. PN-EN 12697-33:2008. *Bituminous Mixtures—Test Methods for Hot Mix Asphalt—Part 33: Specimen Prepared by Roller Compactor*; PKN: Warsaw, Poland, 2008.
56. PN-EN 12697-22:2008. *Bituminous Mixtures—Test Methods for Hot Mix Asphalt—Part 22: Wheel Tracking*; PKN: Warsaw, Poland, 2008.
57. PN-EN 13108-20:2016-07. *Bituminous Mixtures—Material Specifications—Part 20: Type Testing*; PKN: Warsaw, Poland, 2016.
58. PN-EN 12697-12:2008. *Bituminous Mixtures—Test Methods—Part 12: Determination of the Water Sensitivity of Bituminous Specimens*; PKN: Warsaw, Poland, 2008.
59. PN-EN 12697-18:2017-07. *Bituminous Mixtures—Test Methods—Part 18: Binder Drainage*; PKN: Warsaw, Poland, 2017.