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Original Scientific Paper

PERFORMANCE OF ASPHALT MIXTURES WITH A NEW TYPE OF RUBBER MODIFIED BITUMEN

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Abstract. *The rubber modified bitumen 45/80-55 (RMB 45/80-55) product has been used in Hungary as bituminous binder for asphalt mix production since 2013. It is a new kind of rubber bitumen manufactured using patented technology. Over the past 8 years, it has been used to construct or renovate more than 100 asphalt road sections. Originally RMB 45/80-55 was used to replace paving grade bitumen 50/70 in some road construction projects. However, asphalt laboratory results and road construction experience showed that its quality can also achieve or in terms of some parameters exceed that of asphalt mixtures manufactured with polymer modified bitumen 25/55-65 (PMB 25/55-65). Primarily, its excellent resistance to low temperatures and fatigue are outstanding, in this respect; it surpasses the results of asphalts made with polymer-modified bitumen. Its favourable fatigue resistance compensates for its lower stiffness; therefore, favourable results were obtained in the case of track structure design too in comparison with PMB. Considering the road construction benefits of this new type of rubber bitumen, as well as the support of the environmentally friendly recovery of waste tyres and fitting into a circular economy, a wider spread of the RMB product is realistically expected in the future.*

Key words: *rubber bitumen, rubber modified bitumen, rubber bitumen bound asphalt, asphalt mechanical laboratory tests, road section monitoring, pavement scaling*

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1. Introduction

Road pavement structures, especially those in direct contact with road vehicles, are becoming increasingly important for their durability, cost-effectiveness, road safety, travel comfort, etc. levels. The other worldwide trend is the pursuit of sustainability in various branches of the national economy. The essence of sustainability is to exploit win-win opportunities, to find and apply tools and solutions that are good for both societies. The improvement of the pavement structure of roads and sustainable development can be set as a joint objective, among others, by using rubber waste in asphalt mixtures.

Ten years ago, about 1.4 to 1.5 billion tyres were produced annually in the world and about the same amount became waste (ETRMA 2011, Sienkiewicz 2012, Presti 2013). This number is equal to approximately 17 million tons. In its publication, the European Tire and Rubber Manufacturers' Association mentioned 324 million sold tires in Europe and five times that around the world, i.e., around 1.62 billion in 2020 (ETRMA 2020). The life cycle and management of these used tires are not entirely solved yet.

Energy recovery utilizes a significant amount; however, it cannot be considered the most favourable method. The utilization of crumb rubber in road construction is a potential method for the material recovery of the rubber component of waste tyres by dry process (crumb rubber is used during asphalt-mixing) or wet process (rubber first blended with the bitumen) (Takallou 1991, Zareh 2006).Wet processes are more commonly used techniques than the dry ones, but they are also limited by application issues and potential health, safety and environment (HSE) difficulties (Burr et al. 2001).

The development of a Hungarian patent for chemically stabilized rubber bitumen (CSRB) a decade earlier can be considered a significant qualitative step forward in this field (Biró et al. 2009). The favourable laboratory and site performance results substantiate stakeholder expectations and operators that asphalt layers with rubber modified bitumen 45/80-55 (RMB 45/80-55) binder will play an important role in Hungarian road technology selection. A manufacturing plant with a capacity of 20,000 tons/year, in operation since September 2020 produces the amount of chemically stabilized rubber bitumen that makes even the export of the binder a realistic option.

This article aims to evaluate and predict the performance of chemically stabilized rubber bitumen and the asphalt (mixtures) produced with it using different methods; its application areas are also identified.

1.1. Types of preliminary testing of experimental technologies

Following the development of a novel road construction material or technology, one of the most important and not always easy tasks is to demonstrate reliably; to confirm that the material or process in question can indeed achieve the expected long-term performance under the synergistic effect of estimated traffic and environmental loads.

The following main options are available for the preliminary verification of the suitability of innovative road construction materials and technologies (Gáspár et al. 2014):

a) computer performance software (running time is extremely short –a few hours -, but the reliability of the results is rather limited due to the moderate accuracy of the inputs),
b) laboratory tests (they require a short time, typically some days; the composition of the test and reference material samples may be close to the planned one, but the loading

conditions, especially environmental loading, are generally significantly different from the actual ones, which has an adverse effect on the accuracy of the results obtained),

c) accelerated load tests (accelerated load testing - ALT - equipment, using artificial traffic, usually provide more accurate results in a few months, however, their reliability is limited by the difficulties of realistically modelling the environmental load),

d) long term monitoring of condition evolution of experimental phases (although it may take more than a decade, this monitoring is the only type of study that can provide fully reliable results on the expected performance of the innovative material or technology).

In characterizing the expected performance of asphalt mixtures made with chemically stabilized rubber bitumen, the processes listed as options a), b) and d) above-provided information that is reported in this article.

2. Utilization of the Rubber Component of Used Tyres in Road Construction

The application of crumb rubber for asphalt-mix production and road construction dates to the 1960s (Caltrans 2006, Presti 2013). In Sweden, a surface asphalt mixture with the addition of a small quantity of ground rubber from discarded tyres as a substitute for a part of the mineral aggregate in the mixture was used. The goal was to obtain an asphalt mixture with improved resistance to studded tyres as well as to snow chains (Presti 2013). During the same period, in the United States, crumb rubber application started by blending it with bitumen followed by maturation times of 45-60 minutes and then using the rubber-bitumen obtained as a binder instead of bitumen (Caltrans 2006, Presti 2013, Zanzotto 1996). It was observed that this method could beneficially change the properties of bitumen. The method used in Sweden is called the dry, while the other used in the USA is called the wet process (Zanzotto 1996, Zareh 2006, Caltrans 2006).

2.1. Dry process

In the dry process, the crumb rubber does not come into direct contact with the bitumen; it is added to the mineral aggregate (Weidong 2007), and then the bitumen is sprayed onto this mixture. In this case, it cannot be considered rubber bitumen, as only a partially reacted system is created. This means that the intense contact time at high temperature between bitumen and crumb rubber is very short, practically limited to the duration of the asphalt mixing. Therefore, the technical character-improving effect of crumb rubber on the binder is significantly less than the elastomer content (i.e., polymer content) of the rubber would allow (Gooswilligen 2000).

In other words, during the application of the dry process, the crumb rubber can be considered as an inactive filler rather than as an active modifier that can significantly improve the properties of bitumen. The beneficial effect of crumb rubber is manifested in the asphalt mixture to a limited extent, even when mixing and road construction are carried out with appropriate technology. It is important that the particle size of the crumb rubber used should fit the structure of the mineral aggregate.

2.2. Wet process

In contrast to the dry process, when the wet process is used, the bitumen and the crumb rubber are first blended resulting in rubber bitumen before the asphalt is mixed. It can be stated that the crumb rubber has 'time to wet'. The crumb rubber swells by adsorption of the oily components of the bitumen. The rate of this swelling process is influenced by the blending parameters (temperature, mixing time and intensity) of the bitumen and the crumb rubber, as well as the chemical composition of both components and the grain size and surface properties of rubber (Caltrans 2006, Fontes et al. 2006). If crumb rubber and bitumen blending occur at high temperatures with intensive stirring for a long time, the swelling of the crumb rubber can be followed by depolymerisation and vulcanization processes, the crumb rubber dissolves in the bitumen (Zanzotto 1996, Gawel 2006 et al.). The swelling and subsequent dissolution of crumb rubber can be demonstrated through rheological characteristics, e.g., the change in viscosity (see Fig. 1) (Sabita 2015, Presti 2013).

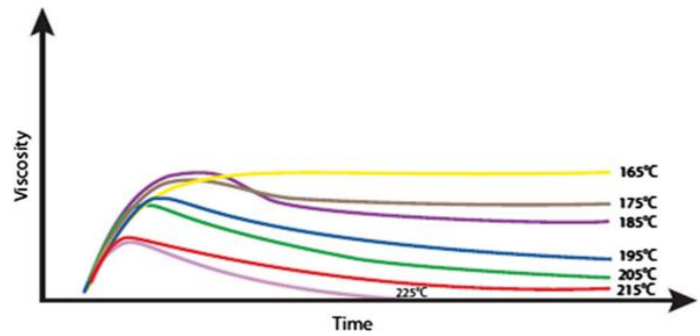

Fig. 1 Change of rubber bitumen viscosity as a function of blending temperature and duration

Several wet process types are known depending on the quality of the rubber bitumen produced and the manufacturing conditions. However, two significantly different rubber bitumen types and their manufacturing technologies can be distinguished (FHWA 2014, Caltrans 2006):

- wet process – high viscosity (rubber bitumen produced at asphalt mixing plant),
- wet process – no agitation (rubber bitumen produced at bitumen factory, sometimes called terminal blend).

2.2.1. Wet process - High viscosity rubber bitumen

The original American manufacturing technology, developed in the 1960s, produces a rubber bitumen product of high viscosity. Production is typically carried out in special rubber bitumen mixing units (e.g., mobile plant installed next to an asphalt mixing plant) typically at 175-200°C for 45-60 minutes (Caltrans 2006). Extender oil can also be used for production, to promote the swelling of the crumb rubber and achieve increased viscosity. As required by ASTM 6114, the viscosity of the rubber bitumen manufactured must be at least 1500 mPas at 175°C. Based on Caltrans data, this viscosity value must be obtained at 190°C. Crumb rubber concentration in the product is up to 15-22 wt% and the particle size used is not bigger than 2.00 mm, or maximum 2.36 mm according to other requirements.

The manufacturing conditions only cause a little dissolution of the rubber crumb; the primary process that takes place is the swelling of the crumb rubber due to the adsorption of certain bitumen components, resulting in an increase in viscosity. If the product is not used immediately, mixing is required during storage due to the intense sedimentation of non-dissolved rubber particles. In this case, due to the dissolution of rubber a decrease in viscosity may occur, which should be improved by blending additional crumb rubber to the rubber bitumen. High viscosity rubber bitumen allows the formation of a significantly thicker binder film on the aggregate surface than conventional bitumen. There are advantages (e.g., a more durable road due to slower aging, a thinner asphalt layer) and disadvantages (special asphalt formula required, more expensive due to higher binder content in the asphalt mixture) of high viscosity rubber bitumen.

The asphalt mixtures and laid asphalt roads containing high viscosity rubber bitumen thus resulted in significant improvements in quality and durability compared to asphalt and roads produced with normal road bitumen (Presti 2013). However, due to the difficulties inherent in the technology and involving special requirements, it is mostly used in the USA only.

2.2.2. Wet process – no agitation rubber bitumen

The application of this technology began in the 1980s in Texas, USA, about 20-25 years later than the production of high viscosity rubber bitumen presented in the previous section. This process uses small, particle sized crumb rubber (up to 0.3 mm), typically 5-10 % by weight, but there are also examples of larger mixing rates (Caltrans 2006, Presti 2013). It is typically manufactured at the site of bitumen production and the product is shipped to the asphalt production site (Caltrans 2006, Shatnawi 2010). The so-called terminal blend is also commonly used for this product, but it can also be manufactured at the asphalt mixing plant and does not need to meet the condition of storage without agitation.

The production, transportation and use at asphalt mixing plant of the agitation-free rubber bitumen product make it similar to PMB. Because of the manufacturing conditions used, the small particle size and the low concentration of crumb rubber, a considerable part of the rubber particles are dissolved in bitumen. It allows the application of the same asphalt formula/composition as the use of PMB. Its similarity to PMB (regarding production, transport, asphalt mixing and asphalt recipe) is an advantage, but the quality of the asphalt mix is below that of the asphalt road built with the rubber bitumen product of high viscosity (Shatnawi 2010). At the same time, it is important to highlight that while no agitation rubber bitumen is used mainly for dense graded asphalt concrete, the high viscosity rubber bitumen product is considered a binder especially for gap-graded or open-graded asphalt types because of its high viscosity. Unlike a high viscosity product, the wet process - no agitation product, like PMB types, can be classified according to the performance grade (PG) system.

3. Rubber Modified Bitumen (RMB 45/80-55) Manufactured by Modified WET Process

The advantages and disadvantages of the two types of rubber bitumen described in Section 3 can be clearly identified. In Hungary, MOL Plc. and the University of Pannonia carried out research and development work on rubber bitumen aiming at efficiently combining the advantages of the two products presented in the previous section and eliminating or at least reducing their disadvantages. The developed new production process, the so-called modified wet process, takes place at the bitumen production site in a specially designed production unit. Based on the relevant patent (Biró et al. 2009), the product is chemically stabilized rubber bitumen (CSRB). In what follows, the RMB 45/80-55 designation is used, as the product is available under this name on the Hungarian bitumen market. The modified wet process by which RMB can be produced is summarized below (Geiger et al. 2012):

In the first technological step, 14-18 wt% (for the final product) crumb rubber below 1.25 mm particle size is added to high-temperature bitumen (>210ºC), then subjected to intense stirring, resulting in swelling and partial dissolution of the crumb rubber.

In the next technological step, the intense mixing of rubber and bitumen continues at a lower temperature (<190ºC). Here a crosslinking additive is also used, which improves the rheological properties of the RMB product. A further advantageous effect of the additive is that it promotes the dispersion of the carbon black and inorganic fillers dissolved from the crumb rubber.

The aim of production technology development was to elaborate a production method to produce rubber bitumen, which possesses the advantages of already known rubber bitumen, has a positive effect on the quality of asphalt roads, and can also be used in the same way as well-known PMB binders. The main condition for applicability identical to PMB is to have the high-temperature viscosity of the product (180°C) similar to that of PMB. This can be achieved if, in addition to the swelling processes of the crumb rubber added to bitumen taking place in the hot bitumen, the polymer components of the rubber are also transferred to the liquid bitumen phase, i.e. the crumb rubber dissolves and acts as an active modifying agent. However, the dissolution of crumb rubber cannot take place completely, because in this case our experience has shown that a loss of quality of the rubber bitumen occurs, and the rubber bitumen produced has asphalt properties similar to those of the original starting bitumen.

For this reason, only an optimal dissolution rate can be allowed, just to the extent necessary to eliminate CSRB usage difficulties. This process can be tracked by checking the viscosity during production; in practice, the on-line measurement of the viscosity change shown in Figure 1 is required. RMB produced by the modified wet process is transported, discharged, and used in asphalt production exactly as in the case of polymer-modified bitumen (PMB 25/55-65). Asphalt mixing, and then paving and compaction are just slightly different from using asphalt produced with PMB since the viscosities of the two binders are almost identical. The aggregate composition of the asphalt is also the same. Thus, it can be concluded that the asphalt production and road construction processes are the same, only PMB is replaced by RMB. During RMB production, the polymers released into bitumen by rubber dissolution improve the properties of bitumen as active modifiers. Unsolved, swollen rubber particles partially retain their elastic properties. As a result, the fatigue and low-temperature properties of the binder are improved, which also has a positive effect on the quality of the asphalt. If the product is used within 24 hours from unloading, it is not necessary to store it in a tank equipped with a mixer, but mixing is required for longer-term storage.

The introduction of the RMB product to the Hungarian market was made more difficult by the fact that RMB 45/80-55 did not meet normal (EN 12591) or modified bitumen (EN 14023) standards either. Due to unsolved rubber particles, plus the carbon black and inorganic filler content released from crumb rubber, the RMB product does not meet the 99.0 wt% toluene solubility requirement set for road construction bitumen in accordance with EN 12591. The cohesion energy and elastic recovery tests required by EN 14023 in the case of PMB products cannot be carried out, as the sample is broken along unsolved rubber particles during stretching. As a result, a new standard (MSZ 930) was developed for the rubber modified bitumen product in Hungary. RMB 45/80-55 meets this standard. The quality requirements, together with the typical quality parameters of the product manufactured in a plant with a capacity of 20 000 t/year in Hungary are shown in Table 1. The existing standard allowed the RMB binder to be included in asphalt standards as an applicable type of binder, so RMB can now be used in road construction in Hungary the same way as well-known paving grade bitumen and polymer modified bitumen products.

Table 1 RMB 45/80-55 quality requirements and typical values

Property	Unit	Requirement (MSZ 930)	Typical values	Method
Penetration at 25ºC	0.1mm	45-80	47-60	EN 1426
Softening point	ºC	≥ 55	58-62	EN 1427
Resistance to hardening				EN 12607-1
Change of mass	%	≤ 0.5	0.05 – 0.2	
Retained penetration	%	≥ 50	70 – 80	EN 1426
Increase in softening point	ºC	≤ 8	3 – 5	EN 1427
Elastic recovery at 25 ºC (*)	%	≥ 50	55 – 70	EN 13398
Fraass breaking point	ºC	≤ -16	-18 - (-22)	EN 12593
Storage stability, difference in softening point (**)	ºC	≤ 8	4 – 6	EN 13399, EN 1427
Flash point	ºC	≥ 235	≥ 280	EN ISO 2592
Dynamic viscosity at 180 ºC	mPas	≤ 500	300-450	EN 13302

(*) Stretching length is equal to 100mm
(**) Storage time at 180ºC is 24 hours

Like the terminal blend rubber bitumen product, RMB is suitable for performance grading (PG) bitumen certifications. In Hungary, it is not required to carry out such tests, but the performance behaviour of RMB is also investigated. The performance grading qualification was done with temperature steps of 3ºC starting at 58ºC at high temperature and -12ºC at low temperature. Table 2 summarizes temperature values where the characteristics of RMB binder reach the required minimum or maximum values. Based on performance grading evaluation RMB 45/80-55 can be classified as PG 76-28 binder. RMB meets the requirement at 76ºC but fails at 79ºC. Similarly, it meets the requirement at -18ºC but fails at -21ºC. (Temperature values presented in Table 2 were determined by logarithmic interpolation.)

Table 2 Performance-related characterization of RMB 45/80-55 used in this article

	Unit	Requirement	Temperature, ºC	Method
Original binder				
Dynamic viscosity	mPas	≤ 3000	127	EN 13302
G*/sinδ	kPa	≥ 1.0	77.4	EN 14770
After Rolling Thin Film Oven Test (RTFOT)				
G*/sinδ	kPa	≥ 2.2	76.4	EN 14770
After Pressure Aging Vessel (PAV) test				EN 14769
G*·sinδ	kPa	≤ 5000	17.3	EN 14770
Stiffness	MPa	≤ 300	-18.2	EN 14771

4. Characteristics of Road Sections Constructed Using RMB

An RMB production plant was established in Hungary in 2012. Using its product, asphalt roads were constructed or rehabilitated over a total length of 150 km on some 110 road sections between 2012 and 2020. The market introduction of RMB in 2012 was preceded by important R&D activities, asphalt testing, and the construction of experimental road sections between 2004 and 2008. During this period, the temporary reconstruction of the existing Hungarian PMB production plant made RMB production possible. A total of five pilot production projects were carried out, and road sections were built at various locations of the Hungarian road network using the five RMB product batches. Positive lessons learned from these road construction projects were the basis to manufacture the RMB product subsequently put on the market in 2012.

During the period between 2004 and 2008, and later in the first years following the start of continuous production in 2012, RMB was exclusively used as a replacement for 50/70 bitumen in asphalt mixing. It was primarily used in the production of AC11 wearing courses and the rehabilitation of minor roads. As experience of use accumulated, more and more inspection results of road section became available over the years. In time, the quality control checks of the wearing courses replaced using RMB confirmed the results of the asphalt laboratory tests, showing that the quality parameters (bearing capacity, cold behaviour, fatigue characteristics, etc.) of asphalts containing RMB binder exceed the quality of asphalt roads constructed using 50/70 bitumen. Besides, favourable road construction experience was also needed for the road construction industry to start using RMB for the rehabilitation and even construction of major roads and motorways.

In 2014, the entire asphalt structure (AC32 base, AC22 wearing and AC11 binder course) of a new 4.2 km long bypass road section of the town of Villány in the southern part of Hungary was built using RMB. A total amount of 21 000 tons of asphalt was mixed for this road construction and 900 tons of RMB binder were used to produce it. The positive achievements gave new momentum to RMB use in road construction, and in the following year, RMB was used in the binder and wearing courses of a 2 km long, shared section of motorways M1 and M7 leading into and out of Budapest, the capital of Hungary. On this section, recycled asphalt was also used in a concentration of 15 wt%. The outcome again reinforced the positive image of RMB.

In the meantime, the product was used in several other minor or major road construction or rehabilitation projects, the method was adopted by a growing number of asphalt companies and road builders, and RMB application eventually became routine. The established routine and favourable technical results confirmed that besides replacing 50/70 bitumen, RMB can also achieve asphalt quality equal or superior to that produced using the polymer-modified bitumen PMB 25/55-65. This allowed RMB to be used instead of PMB 25/55-65 first in 2019 and then repeatedly in 2020 for the construction of new motorway sections. In 2019, all three asphalt layers (SMA 11 wearing, AC 22 binder, AC 32 base course) on a 2 km long section of motorway M25 were constructed using asphalt mixtures containing RMB. In 2020, RMB was also used for the construction of an expressway, a 5.6 km long section of the M76 motorway. Here a total of 1,400 tons of RMB was used to construct 2x2 lanes laying a base (AC32) and a binder course (AC22).

Of the more than 110 sections built so far, 32 experimental and 3 (conventionally composed) reference sections were field-tested on-site in 2019. This covered the visual characterization of pavement conditions and the classification of the macro roughness of pavement surface. Also, the deflection of the pavement structure was characterized in 9 experimental and 2 reference sections.

Surface conditions (defects) and the sand patch type macro roughness of the pavement surface were characterized on the road sections with wearing courses built between 2012 and 2017 (i.e., 2-7 years old at the time of measurement) with rubber bitumen binder. Without access to the very small number of actual reference sections built, the registered condition marks of rubber-asphalt wear layers were compared to those of the standard trial sections monitored in Hungary yearly for almost 30 years (Road Management 2018) according to the following steps:

- classification of the experimental sections – small (max. 1500 unit vehicle/day), medium (1501-5000 unit vehicle/day), or large (min. 5001 unit vehicle/day) – into traffic categories, 5-stage assessment of the pavement condition of the experimental sections in 2019,
- determination of the annual average condition mark scores of the three traffic categories for various pavement ages,
- determination of the values corresponding to varying pavement ages of the surface integrity (defect) pavement performance models within the appropriate road section classes of the standard trial sections condition monitored since 1991 (Road Management 2018),
- comparison of the mean values of the corresponding rubber asphalt sections and the pavement performance model values of the trial sections with "conventional" composition (as an example, see Table 3),
- carrying out the same steps for the macro roughness of pavement surface after converting sand depths to 5-grade condition marks (Table 4),
- the reported condition notes for surface defects can be calculated by the algorithms of the Roadmaster keyboard defect collection device (e-ÚT 09.02.26 road technical specification), while for the macro roughness the values of sand depth can be calculated with the algorithms according to MSZ EN 13036-1: 2010,
- in Tables 3 and 4, the pavement performance model values are averages; Table 5 shows the mean, standard deviation, and relative standard deviation of the underlying data sets.

Table 3 Comparison of deterioration rates of medium traffic volume sections

Experimental sections		Reference sections		Difference
Age (year)	Mean grade	Age (year)	Mean grade	
7	3.0	7	3.6	-0.6
5	2.0	5	2.2	-0.2
4	1.9	4	1.9	-0.0
3	1.2	3	1.7	-0.5

In the other two traffic categories, the average surface texture rating of the rubber bituminous binder wearing courses determined by age group was again generally more favourable than the corresponding values of the standard sections chosen for reference, and only infrequently were they the same.

The average, macro roughness grades of the tested rubber-asphalt road sections by traffic category were in all cases better than the averages of the corresponding reference sections. (The time series obtained after converting the macro texture values determined from the national public road network and monitored annually since then with a laser RST measuring car (e-ÚT 09.02.24) into 5-mark grades was chosen as the basis of comparison).

Table 4 Comparison of relevant macro roughness values of pavements

Traffic category	Experimental sections		Reference sections		Difference
	Age (year)	Mean grade	Age (year)	Mean grade	
Small	7	2.8	7	3.1	-0.3
	6	2.5	6	2.6	-0.1
Medium	7	3.0	7	3.8	-0.8
	5	2.7	5	3.7	-1.0
Heavy	5	3.5	5	3.7	-0.2
	4	2.7	4	3.4	-0.7

Table 5 Average, standard deviation, and relative standard deviation of data sets behind selected points of performance models

Point of performance model	Mean value	Standard deviation	Relative standard deviation
Surface defects, medium traffic, 7 years	3.6	0.36	0.10
Surface defects, medium traffic, 5 years	2.2	0.21	0.10
Surface defects, medium traffic, 4 years	1.9	0.10	0.05
Surface defects, medium traffic, 3 years	1.7	0.11	0.06
Macro roughness, small traffic, 7 years	3.1	0.40	0.13
Macro roughness, small traffic, 6 years	2.6	0.27	0.10
Macro roughness, medium traffic, 7 years	3.8	0.39	0.10
Macro roughness, medium traffic, 5 years	3.7	0.36	0.10
Macro roughness, heavy traffic, 5 years	3.7	0.29	0.08
Macro roughness, heavy traffic, 4 years	3.4	0.27	0.08

The dynamic falling weight bearing capacity (deflection) measurement performed with KUAB equipment on 3 experimental sections were compared - in pairs - with their neighbouring references (identical pavement structure but with traditional binder). The results obtained here have shown that the average deflections of the reference sections were on average by 10% higher.

5. Related Laboratory Asphalt Tests

The BUTE (Budapest University of Technology and Economics) Highway and Railway Department and the KTI Institute for Transport Sciences Non-Profit Ltd. have participated without interruption in the analyses of asphalt mix with rubber bitumen almost since the beginning of development work in 2008. As early as 2009, they tested rubber bitumen mixture according to earlier technical specifications with promising results. These earliest tests revealed it right away that the asphalt mixture with rubber bitumen had better asphalt mechanical characteristics than the asphalt mixture with traditional road bitumen (better fatigue resistance and plastic deformation); it was found that some of its features almost reached or even outperformed the features of the polymer-modified bitumen (PMB) mixture. Over the last decade or so, we performed the particular asphalt mechanical tests on different asphalt mixtures applying three types of bitumen bonding. The key results obtained are highlighted below (Almássy et al. 2009).

This section summarizes the results of asphalt mechanical tests carried out over the past five years on asphalt specimens (test pieces) manufactured under laboratory conditions or on samples drilled on-site after several years of operation.

5.1. Applied bitumen types and results of conventional bitumen testing

In the tests, 50/70 paving grade bitumen, RMB 45/80-55 rubber modified bitumen, and PMB 25/55-65 modified bitumen by linear SBS elastomer were used as bituminous binders. These bitumen types are characterized by the quality parameters presented in Table 6.

Table 6 Results of conventional bitumen tests on different bitumen types (Tóth et al. 2016, Tóth et al. 2017, Gáspár et al. 2019)

Properties	Bitumen 50/70	RMB 45/80-55	PMB 25/55-65
Softening point, °C	50.2	62.0	78.0
Penetration, 0,1mm	55	47	32
Fraass breaking point, °C	-17	-21	-20

5.2. Asphalt mixtures used for testing

The following asphalt mixtures were used for laboratory testing between 2016 and 2019:

- AC 11 wearing course, with B50/70 conventional bitumen (as control mixture), with PMB 25/55-65 polymer modified bitumen (as control mixture), with RMB 45/80-55 rubber modified bitumen (rubber bitumen modified asphalt mixture) – testing year: 2016;
- AC 16 binder course (mI), with PMB 25/55-65 polymer modified bitumen (as control mixture), with RMB 45/80-55 rubber modified bitumen (rubber bitumen modified asphalt mixture) – testing year: 2017;
- AC 22 binder course (mI), with PMB 25/55-65 polymer modified bitumen (as control mixture), with RMB 45/80-55 rubber modified bitumen (rubber bitumen modified asphalt mixture) – testing year: 2017;
- SMA 11 wearing course (mI), with PMB 25/55-65 polymer modified bitumen (as control mixture), with RMB 45/80-55 rubber modified bitumen (rubber bitumen modified asphalt mixture) – testing year: 2017;
- SMA 11 wearing course, with PMB 25/55-65 polymer modified bitumen (as control mixture), with RMB45/80-55 rubber modified bitumen (rubber bitumen modified asphalt mixture) – testing year: 2019.

Table 7 presents the bituminous binder types applied and concentrations used for asphalt mixture production.

Table 7 Bitumen content of the tested asphalt mixtures. (Tóth et al. 2016, Tóth et al. 2017, Gáspár et al. 2019)

Name of the asphalt mixtures, (Testing year)	Bitumen content (m%)	Comments
AC 11 wearing course (2016)	5.1 %	
AC 16 binder course (mI) (2017)	4.5%	
AC 22 binder course (mI) (2017)	4.2 %	
SMA 11 wearing course (mI) (2017)	6.2%	0,5 % runoff inhibitor additive
SMA 11 wearing course (2019)	6.2%	

All mixtures are designed for high traffic resistance and their use is widespread both in Hungary and in many other European countries. Differences between traditional bitumen, polymer and rubber-modified binders have resulted in slightly different bulk density, voids free (maximum) bulk density and air voids per mixture types. The results of the air void content of asphalt mixtures with different bitumen binder type and identical aggregate structure and source are shown in Figure 2.

The asphalt mixtures prepared appear to meet the requirements of the new regulation, where the intended air void content may be 2.5-4.0% for SMA 11 (mI) mixtures, 2.5-4.5% for AC 11 wearing course mixtures and 3.0-5.0% for AC16 (mI) and AC22 (mI) mixtures. So, the difference in air void content is not significant, and does not play a decisive role in the test results presented below (see Fig. 2).

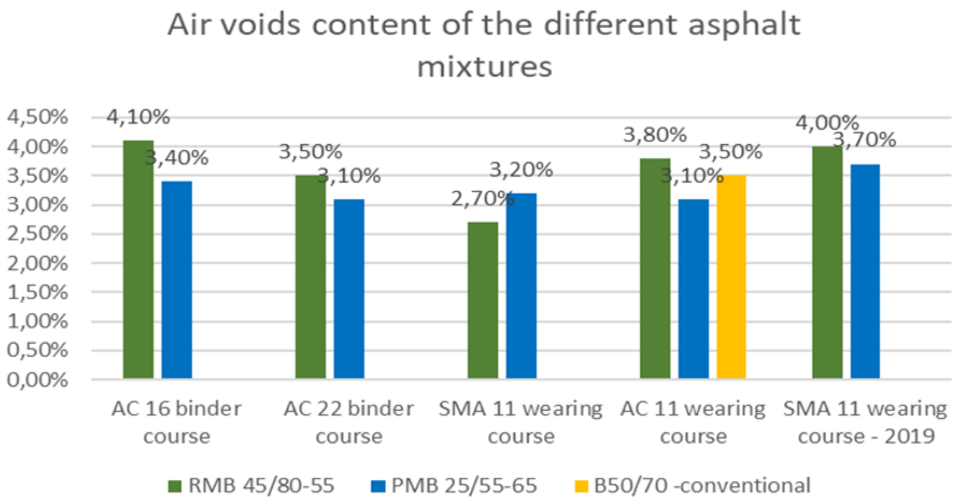

Fig. 2 Air void content of the asphalt mixtures with different binder types, otherwise identical mix volumetrics

Table 8 shows the particle size distribution of each mixture, which complies with the Hungarian technical specifications.

Table 8 Particle size distribution of mixtures used in the tests

Sieve size (mm)	Percentage passing (%)	Percentage passing (%)	Percentage passing (%)	Percentage passing (%)	Percentage passing (%)
	AC 11 wearing course (2016)	AC16 (mI) binder course (2017)	AC22 (mI) binder course (2017)	SMA11 (mI) wearing course (2017)	SMA 11 (mI) wearing course (2019)
31,5	100	100	100	100	100
22,4	100	100	97	100	100
16	100	99	73	100	100
11,2	98	69	52	94	95
8	71	58	46	55	56
5,6	56	46	40	43	46
4	46	37	33	36	36
2	36	26	21	24	26
1	24	18	16	18	19
0,5	18	16	15	15	16
0,25	14	12	11	14	14
0,125	11	10	10	12	12
0,063	8,0	8	7,9	10	10

5.3. Results of asphalt mechanical tests

In 2016 and 2017, in the laboratory of Budapest University of Technology and Economics, stiffness, wheel tracking and low temperature cracking tests using AC 11 wearing course, AC 16 binding course (mI), AC 22 binding course (mI) and SMA 11 wearing course (mI) with the application the above-mentioned bitumen binders were performed. (According to the Hungarian standard, the mI symbol refers to the use of a mixture of modified bitumen for intensive roads of highest traffic load category). In 2019, bending-fatigue tests were carried out to determine the SMA 11 wear-ing course fatigue life. In 2019, bending-fatigue tests were carried out to determine the SMA 11 wearing course fatigue life and stiffness values were measured in bored specimens that had been built in several years before.

5.3.1. Stiffness tests

The stiffness tests were performed at 20°C according to the EN 12697-27 standard (Bituminous mixtures – Test methods for hot mix asphalt – Part 26: Stiffness) on AC 11 wearing course asphalt mixtures. These test results show that asphalt mixtures containing RMB may achieve a higher stiffness value than asphalts mixed with conventional 50/70 bitumen, but do not reach the stiffness values of the asphalt mixtures containing a PMB binder (Fig. 3) (Tóth et al. 2016).

The results obtained for the bored specimens in IT-CY stiffness tests in 2019 showed that the stiffness values of RMB-mixtures were between 3000 and 4000 MPa, while the stiffness value of the reference sections with polymer-modified bitumen mixtures could reach 4446 and 5285 MPa stiffness. It follows that the stiffness of PMB binder mixtures was 30% higher than that of RMB’s. In Figure 4, rubber bitumen mixture stiffness results are traced in green, whereas polymer modified mixtures stiffness results selected for reference are shown in blue (Fig 4).

The test involved an urban main road, Grassalkovich Street (built with the use of RMB-asphalt mixtures in 2014), and the road section on Road no. 7410 in Zalaegerszeg (built with RMB and PMB asphalt mixtures in 2012). Choosing Road no. 7410 in Zalaegerszeg was justified by the motivation that their RMB and PMB binder wearing courses were paved at the same time. The urban main road (Grassalkovich Street), built in 2014, was chosen because it carried the same traffic as Road no. 7410 in Zalaegerszeg. (Gáspár et al., 2019).

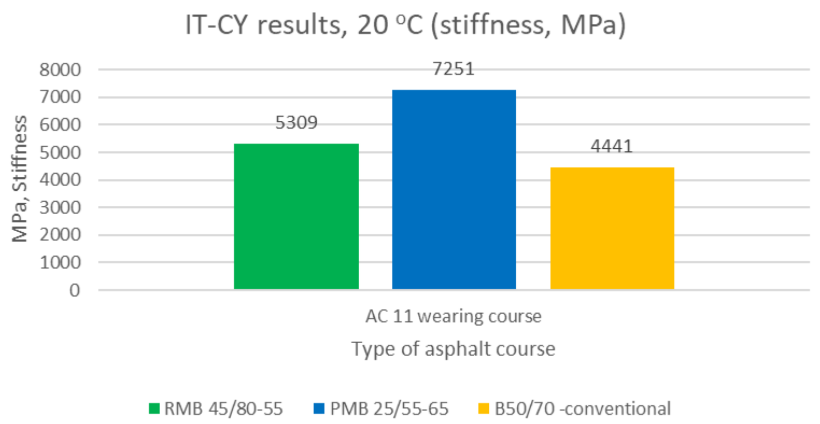

Fig 3. Results of the IT-CY test at 20°C. (Tóth et al. 2016)

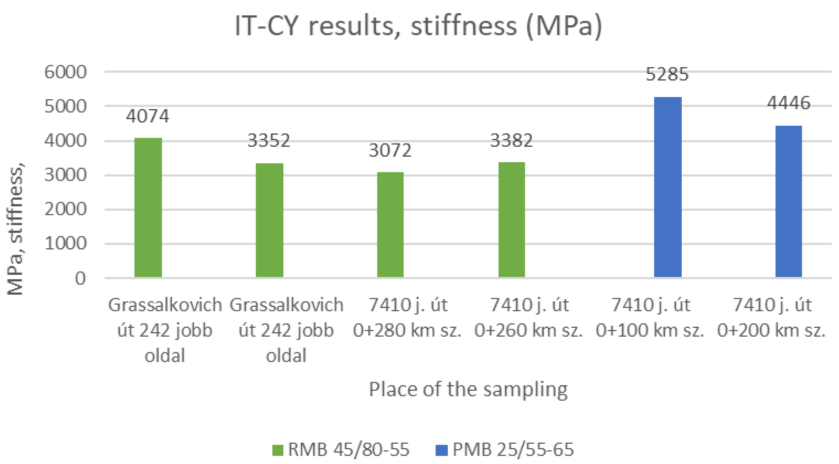

Fig. 4 RMB (green) and PMB asphalt mixture (blue) results for drilled specimens. (Gáspár et al. 2019)

5.3.2. Wheel tracking plastic deformation tests

The wheel tracking tests very well representing plastic deformation characteristics were performed according to the EN 12697-22 standard (procedure B, small specimen) at 60°C (EN 12697-22 2003). After the examination of practically all mixtures, it can be concluded that wheel tracking test results show excellent plastic deformation characteristics for rubber bitumen modified mixtures since for them the wheel tracking depths obtained were much smaller than those for polymer modified or conventional B50/70 bitumen mixtures (Fig. 5) (Tóth et al. 2016, Tóth et al. 2017).

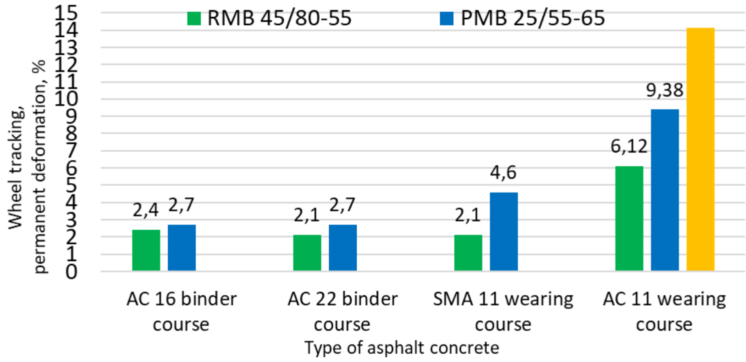

Fig. 5 Results of wheel tracking test (Tóth et al. 2016, Tóth et al. 2017)

5.3.3.. Low-temperature behaviour – resistance to cracking at low temperatures

With the excellent wheel tracking formation (rutting) properties of rubber bitumen mixtures in mind, it was normally expected that due to increased stiffness and plastic resistance, the low crack resistance of rubber bitumen mixtures would not be so outstanding. Nevertheless, for all asphalt mixtures tested, the cracking temperature of the mixture with rubber bitumen was the lowest, far outstripping the cracking temperature of mixtures made with polymer and conventional bitumen (Fig. 6). Low temperature crack resistance tests were carried out in compliance with technical standard EN 12697-46 (thermal stress restrained specimen test - TSRST test) (EN 12697-46 2012). It is important to note that the height and thickness of the test pieces were a non-standard 50 mm, and their length was 250 mm (Tóth et al. 2016, Tóth et al. 2017).

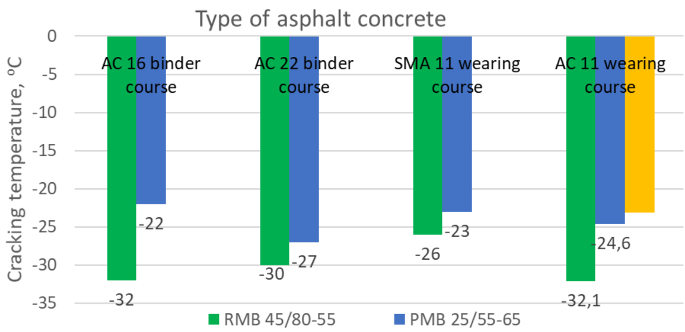

Fig. 5 Cracking temperature results for asphalt mixtures tested (Tóth et al. 2016, Tóth et al. 2017)

5.3.4. Fatigue resistance test

In the 2017 study, the fatigue resistance of asphalt mixtures AC 16 (mI) base, AC 22 binder (mI), and SMA 11 wearing (mI) was tested, while in the 2019 research SMA 11 wearing asphalt mixtures were tested (Fig. 7). In all cases, the tests were carried out at a test temperature of 20 °C and a frequency of 30 Hz, according to the relevant Hungarian road technical regulation (e-UT 05.02.11), in the analysis of test results the deformation value corresponding to the load repetition number of 10^6 was considered. In accordance with the standard EN 12697-24, the specimen geometry of fatigue resistance test is the following:

- SMA 11 wearing course: 5 cm high, 5 cm wide and 50 cm long,
- AC 16 binder course: 7 cm high, 7 cm wide and 50 cm long,
- AC 22 binder course: 7 cm high, 7 cm wide and 50 cm long.

Although the specification for the requirements of mixtures of asphalt paving (e-UT 05.02.11) does not contain a value to be achieved for the fatigue of stone mastic asphalt, the minimum values in the specification are 110 and 130 μstrain, respectively. Regarding the test results of fatigue resistance, it can be clearly stated that for all asphalt mixtures of different types, binder mixtures modified with rubber bitumen achieved better results and longer fatigue life than polymer-modified binder mixtures.

Compared to earlier fatigue tests carried out on other asphalt mixtures, it is observed that in 2019 the fatigue resistance of the rubber modified bitumen (RMB binder) SMA 11 wearing asphalt mixture turned out to be extremely high, namely 328 μstrain (Gáspár et al. 2019).

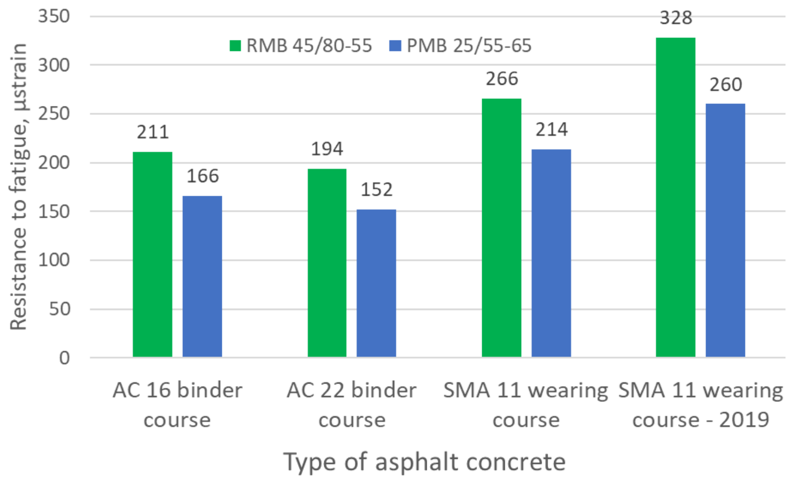

Fig. 7 Fatigue resistance of asphalt mixtures tested (Gáspár et al. 2019)

6. PAVEMENT STRUCTURAL DESIGN

Using the principles of mechanical pavement structural design, it is possible to compare the material characteristics and behaviour of the various asphalt mixtures (Brown 2013, Cho et al. 2018, Cho et al. 2020). The performance of the different asphalt mixtures within the pavement structure can be detected in unit axis passes (pcs) or in the required asphalt thickness (mm). To perform the calculations, a pavement structure model is needed, where the mechanical performance of each layer is given by its characteristic elasticity modulus (E), Poisson's ratio (μ), and layer thickness (*h*). In addition, the degree of inter-layer interaction should be recorded (Tóth et al. 2020).

When solving the design task, it is generally understood that these loads are known only in the axis of wheel load on the surface of the top layer, at critical locations, as these will be critical. In the case of asphalt mixtures, the fatigue criterion is that the horizontal (ε_t) strain arising in the bottom zone of the lowest asphalt layer is critical.

Complex and cumbersome calculations can be performed with structural design programs such as Shell BISAR or WESLEA (De Jong et al. 1979, Timm 2006). It was felt that the application of BISAR and WESLEA programs in the case of asphalt layers with non-conventional binders could have been used with due care. However, the aim of the model calculations in this case was to be able to demonstrate the extremely complex effect of different asphalt characteristics (especially their magnitude and direction) by quantifying them with some easily interpretable parameters. The obtained values of the model calculations are, of course, relative values, they cannot be generalized. It is reassuring, however, that the results of the calculations are in good agreement with the experience gained during experimental section monitoring, confirming them as if they were "validated". Of course, further research is needed to fully validate the model calculations for scientific purposes.

These software tools primarily determine stresses at any point in the model. For the calculation of specific deformations, it is assumed that the deformation is proportional to the stresses and thus the equations of Hooke's law adapted for the general spatial stress state apply. These equations can be used to calculate the specific deformation at any test point if the stress state of the point, plus the elastic modulus and Poisson's ratio of the layer are known. However, to understand the magnitude of specific deformations, one needs to know the fatigue behaviour of the material. Considering the appearance of fatigue cracks, the value of the ε_t (N) allowed limit strain corresponding to design traffic can be found from the Wöhler-curve of the material (Primusz et al. 2018).

The laboratory-defined parameters of the three asphalt mixtures included in the test are summarized in Table 9 (Primusz et al. 2020).

Table 9 Material parameters of asphalt mixtures

Mixture	Young's modulus [MPa]	Poisson's ratio [-]	ε_t (*N*) allowed strain [µs]
AC 22 binding course, B50/70	4 440	µ = 0.35	135
AC 22 binding course, PMB 25/55-65	7 250	µ = 0.35	152
AC 22 binding course, RMB 45/80-65	5 310	µ = 0.35	194

The performance of asphalt mixtures with different binders but with the same aggregate grading is presented in the pavement structure through the construction of a characteristic flexible pavement structure. It is common in all structures that the asphalt wearing course (4 cm and 4000 MPa) and the granular (FZKA) base layer (25 cm and 350 MPa) are made of the same material with identical thickness, assuming the same subgrade bearing capacity (50 MPa). (Marking FZKA means a continuously graded, unbound, crushed stone road base). The main difference between the three structures is introduced through the different material parameters of the asphalt binder course and the upper base course (20 cm) according to Table 6. Full bond between asphalt layers and full slip between asphalt and granular layers are assumed. The most important details of the three pavement dimensioning options are shown in Table 10 and illustrated in Fig. 8.

Table 10 Flexible pavement structure dimensioning option with of FZKA lower base course

Layer	Thickness [mm]	Young's modulus [MPa]			Poisson's ratio [-]	Interlayer adhesion
Asphalt wearing course	40	4 000			0.35	Full bond
Asphalt binder course and upper base course together	200	B50/70 4 440	PMB 7 250	RMB 5 310	0.35	Full slip
FZKA base course	250	350			0.40	Full bond
Subgrade	infinite	50			0.45	

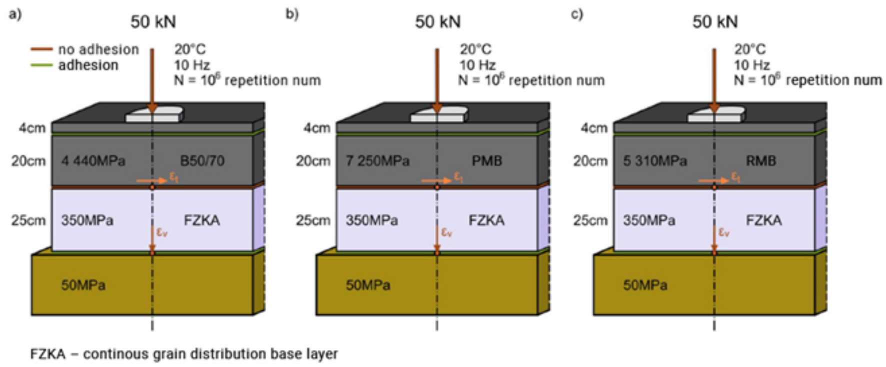

Fig. 8 Flexible pavement structure design options applied to the three test mixtures.

The standard and allowed strains of the structures characterized by the three mixtures are shown in Table 11.

Table 11 Standard strains (FZKA) in the bottom zone of asphalt binder course and of upper base course

Asphalt mixture	Standard strain, ε_t [μs]		Allowed strain, ε_t (N)
	BISAR	WESLEA	[μs]
50/70	201,0	205.9	135
PMB 25/55-65	137,5	140.3	152
RMB 45/80-65	175,4	179.6	194

According to mechanical model calculations, the mixture containing the conventional 50/70 penetration grade bitumen DOES NOT COMPLY, while the bitumen modified with polymer or rubber does. To express the differences between mixtures more visually (in asphalt thickness), it is advisable to change the thickness of the lowest asphalt layer until the standard horizontal specific strain (ε_t) coincides with the allowed limit value $\varepsilon_t(N)$. Three equivalent structures are then produced for fatigue cracks. The calculations were carried out with BISAR software, the combined thickness of the equivalent structures with asphalt binder course and the upper base course is shown in Table 12 and the dimensioning options are graphically introduced in Fig. 9.

Table 12 Need for asphalt thickness in three equivalent structures (FZKA*)*

Mixture	Standard ε_t [μs]	Allowed $\varepsilon_t(N)$ [μs]	Thickness [mm]	Difference [mm]
B50/70	134,0	135	265	+65 mm
PMB 25/55-65	153,2	152	185	-15 mm
RMB 45/80-65	194,5	194	185	-15 mm

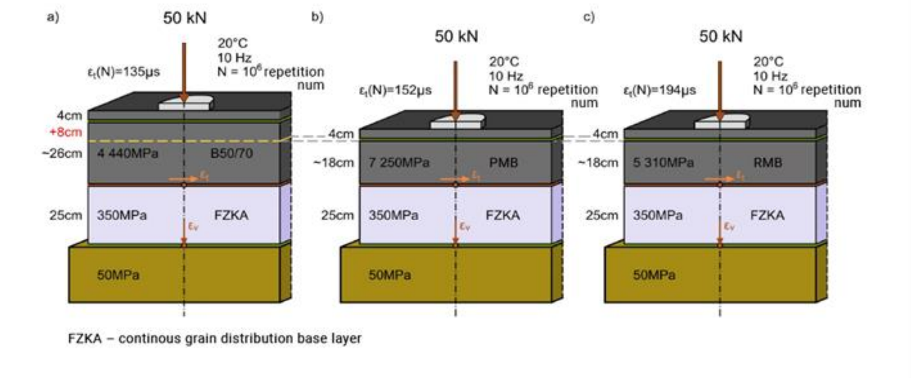

Fig. 9. The three equivalent flexible road structure models (FZKA)

For an asphalt mixture containing traditional performance grade bitumen, a 26.5 cm thick layer is required for a number of unit axle passes of 10^6, whereas for a mixture modified with polymer and rubber only an 18.5 cm thick layer is necessary resulting in practice in 8 cm asphalt saving. The calculation also demonstrates that the higher elastic modulus of the polymer-modified mixture is well compensated by the better fatigue properties of the rubber-modified mixture. The calculation presented for the granular (FZKA) lower base course was also repeated for the much stiffer lower base course of hydraulically bound stabilization (C_{Kt}). The layout of the structures is given in Table 13.

Table 13 Flexible pavement structure design option for C_{Kt} base course

Layer	Thickness [mm]	Young's modulus [MPa]			Poisson's ratio [-]	Interlayer adhesion
Asphalt wearing course	40	4 000			0,35	Full bond
Asphalt binder course and upper base course together	200	B50/70 4 440	PMB 7 250	Full slip 5 310	0,35	25% bond
C_{kt} base course	200	2 000			0,40	Full bond
Subgrade	infinite	50			0,45	

Design task has been solved again with BISAR and WESLEA programs, the standard and allowable strains of the three mixtures are shown in Table 14.

Table 14 Standard strains (C_{Kt}) in the bottom zone of asphalt binder course and of upper base course

Mixture	Standard strain, ε_t [μs]		Allowable strain, $\varepsilon_t(N)$ [μs]
	BISAR	WESLEA	
50/70	171.0	173.3	135
PMB 25/55-65	122.6	126.1	152
RMB 45/80-65	152.0	154.8	194

According to mechanical model calculations, even for the lower base course, $C_{kt,}$ only the conventional mixture containing 50/70 penetration, performance grade bitumen does not comply. To express the differences between mixtures more graphically (in asphalt thicknesses), the thickness of the lowest asphalt layer was changed until the standard horizontal specific strain coincided with the $\varepsilon_t(N)$ allowable limit. The required asphalt thicknesses of the asphalt mixtures included in the test are summarized in Table 15.

Table 15 Need for asphalt thickness of the three equivalent structures (C_{Kt})

Mixture	Standard ε_t [μs]	Allowable $\varepsilon_t(N)$ [μs]	Thickness [mm]	Difference [mm]
B50/70	135,4	135	245	+45 mm
PMB 25/55-65	150,2	152	165	-35 mm
RMB 45/80-65	195,8	194	150	-50 mm

Due to the stiffer hydraulically bound stabilization, the upper asphalt base course containing B50/70 performance grade bitumen requires only 4.5-5.0 cm of additional asphalt thickness in the case of 10^6 unit axle passes. The upper asphalt base courses with bitumen modified with polymer and rubber, in turn, result in significant asphalt savings. The interesting thing about the dimensioning case study is that for the stiffer lower base course, the difference between PMB and RMB mixtures can already be expressed in cm. The asphalt layer containing rubber-modified bitumen requires less asphalt thickness by 1.0-1.5 cm. In addition to the thinner asphalt top base course, this may also mean that the RMB mixture should be chosen when stiffer lower base layers are applied. This assumption can be confirmed unambiguously by future additional laboratory measurements and case study calculations. However, the results of modelling show that the mere fact that a mixture has a given, high or low stiffness and the magnitude of its fatigue resistance does not give a complete picture of the mixture, the conformity of the mixture can only be determined comprehensively when examined as a pavement structural layer (Primusz et al. 2020).

7. Conclusions

The RMB 45/80-55 binder presented in this article is a novel, rubber bitumen product type, which - as described here - is produced by the so-called modified wet process instead of the already familiar conventional wet processes. Due to its manufacturing technology and composition, RMB carries certain characteristics of both high viscosity rubber bitumen and terminal blend type rubber bitumen. During its development, the goal was precisely to eliminate or to reduce the disadvantages and to preserve the advantages of the latter. One of the key quality parameters of the product is dynamic viscosity, the value of which allows RMB to be used in transport, unloading, pumping, asphalt production, and road construction the same way as polymer-modified bitumen types are. User appreciation over the past 8 years and construction experience gained from more than 110 constructed road sections have been favourable. Given this information, a comprehensive review of some of the roads built was carried out.

During the on-site pavement condition survey covering 35 road sections completed in 2019, the deterioration rates of pavement surface condition and macro roughness were better in the RMB sections than in the reference sections in all traffic categories. The pavement structure bearing capacity (deflection) values measured on sections at least 4 years old proved to be extremely favourable on all RMB sections examined. The promising research results confirmed the wide applicability of the RMB asphalt mixture. It can offer an economic, durable, and environmentally friendly solution for the construction of a wearing, a binder, or a base course in the national highway network, the municipally managed (local) road network, and in the case of paving areas.

Laboratory tests of different types of asphalt mixtures were carried out between 2016 and 2019 at the Budapest University of Technology and Economics. Traditional B50/70 bitumen was initially used as a reference binder; these results clearly showed that the parameters of each test of rubber bitumen mixtures were found to be superior to mixtures made with conventional performance grade bitumen. The results of subsequent asphalt mechanical tests showed that, for each type of asphalt selected, the rubber bitumen binder mixture produce better cold behaviour, fatigue resistance, and rutting resistance than the polymer-modified binder mixtures do. Laboratory mixtures and on-site bored samples had stiffness test results preferable than polymer modified binder mixtures do.

Simple modelling was used to test the structural layer behaviour of mixtures made with three different binders separately. Polymer modified bitumen (PMB 25/55-65), rubber modified bitumen (RMB 45/80-55), and performance grade bitumen (50/70) were studied. The model calculation demonstrated that the binder and asphalt mixture tests alone and the ratings based on them provide very limited information on their behaviour in pavement structures. Incorporation of a less stiff but outstandingly fatigue resistant mixture into an appropriate pavement structure layer may result in a significant – and quantifiable – increase in pavement lifespans or a reduction in thickness, while a layer with a stiffer but average fatigue resistant mixture may have a shorter life. These relationships remain hidden when worldwide standard pavement structures are applied; thus, their exposure is not possible by purely empirical means.

As a summary, the favourable behaviour of the asphalt layers with GmB binder could have been determined based on the concurrently favourable results of section monitoring and laboratory experiments. It is planned to increase the reliability of the statement with additional laboratory and field measurements planned soon.

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PERFORMANSE ASFALTNIH MEŠAVINA SA NOVIM TIPOM BITUMENA MODIFIKOVANOG GUMOM

Bitumen modifikovan gumom 45 / 80-55 (RMB 45 / 80-55) se u Mađarskoj koristi kao bitumensko vezivo za proizvodnju asfaltne mešavine od 2013. To je nova vrsta gumenog bitumena proizvedena po patentiranoj tehnologiji. U proteklih 8 godina korišćen je za izgradnju ili renoviranje više od 100 asfaltnih deonica. Prvobitno je RMB 45 / 80-55 korišćen za zamenu bitumena za asfaltiranje 50/70 u nekim projektima izgradnje puteva. Međutim, laboratorijski rezultati asfalta i iskustvo u izgradnji puteva pokazali su da njegov kvalitet može dostići i po nekim parametrima premašiti kvalitet asfaltnih mešavina proizvedenih s bitumenom modifikovanim polimerom 25/55-65 (PMB 25/55-65). Prvenstveno, njegova odlična otpornost na niske temperature i zamor su izvanredni, u tom pogledu; nadmašuje rezultate asfalta izrađenih s bitumenom modifikovanim polimerom. Njegova zadovoljavajuća otpornost na zamor kompenzuje manju krutost; stoga su i kod projektovanja gazne konstrukcije postignuti povoljni rezultati u odnosu na PMB. Uzimajući u obzir prednosti kod izgradnju puteva ove nove vrste gumenog bitumena, kao i podršku ekološki prihvatljivom recikliranju otpadnih guma i uklapanju u cirkularnu ekonomiju, realno se očekuje veće širenje RMB proizvoda u budućnosti.

Ključne reči: *gumeni bitumen, gumeni modifikovani bitumen,gumeni asfalt vezan bitumenom, laboratorijska mehanička ispitivanja asfalta, osmatranje deonice puta, ljuštenje habajućeg sloja*