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Performance assessment of full depth asphalt pavements manufactured with high recycled asphalt pavement content

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Abstract: Reclaimed asphalt pavement (RAP) is generated during road rehabilitation and resurfacing projects. This highly valuable recycled material should be used for manufacturing fresh hot mix asphalt (HMA) for new asphalt pavement layers to ensure the highest added value and minimise environmental impact. The use of RAP is already common practice worldwide; however, incorporating RAP into the manufacturing of HMA is still very minimal in Hungary. As part of a research work HMA containing 20-50% RAP was designed, manufactured and tested. This paper discusses the performance tests carried out on laboratory and plant mixed asphalt mixes; using this data the overall full depth asphalt (FDA) pavement performance was predicted through general mechanistic pavement design. The outcomes of this paper showed that high RAP content asphalt mixes can have superior performance; this disproves the common perception that high RAP mixes are substandard road construction materials. The analysis performed in this paper found that asphalt mixes with high RAP content present low risk for in-situ performance. However, in order to achieve this outcome, the application of correct mix design methodology, appropriate RAP management and suitable asphalt plant capability for mass production are paramount.

Keywords: performance; pavement design; recycled asphalt pavement

I. INTRODUCTION

Reclaimed asphalt pavement (RAP) is generated during road rehabilitation and resurfacing projects through cold milling or breaking up layers, which is quite often used then for lower base layer or shoulder works in Hungary. This approach is not considered the best application from a national economy perspective, as it should be ensured that recycled materials are incorporated into newly constructed road pavement layers at the highest possible level, i.e. road base material in road base and asphalt material in asphalt layers. This is to ensure that the energy embedded in the relevant layer during the original manufacturing and construction activity is not lost or the loss is minimised. The most obvious solution to this problem is the use of asphalt mixes manufactured with the addition of RAP.

The use of RAP is already common worldwide at a fairly large level in the asphalt lower base, base and intermediate (binder) layers; there is still a lot of potential increasing the RAP content especially in the wearing course applications [1].

Unfortunately incorporating RAP into the manufacturing of new hot mix asphalt (HMA) is still very minimal in Hungary, despite the obvious economic advantages and developments in asphalt manufacturing technologies in the last two decades. In Germany and France huge quantities of RAP have been used for the production of HMA at asphalt mixing plants. Based on latest figures from the European Asphalt Pavement Association [2], 11.6 million tons of RAP was used in Germany and 6 million tons in France in 2021. In Hungary, this volume was 157,000 tons, which means that in average only 3.2% of the total asphalt production contained RAP. The average recycling rate in Germany was 25.6%, while in France this value was 12.8%. **Table 1** provides a summary of these figures where the neighbour country, Austria is also highlighted; average RAP usage was 10.5% in Austria. In the United States (US) RAP usage increased from an average of 15.6% in 2009 to an average of 21.9% in 2021. Given the US is a very large country with an extensive road network the total RAP usage was accordingly a total of 94.6 million tonnes in 2021 [3]. A study tour conducted by US researchers in December 2014 in Japan revealed that the country produces 55 million tonnes of asphalt and the average RAP usage was 47%. There was a significant increment in usage since 2000 when the average RAP usage was 33% [4]. No recent has been data published for Japan, therefore this latest data set was not added to the summary (**Table 1**).

Table 1. *Hot mix asphalt and recycled asphalt pavement usage in various countries in 2021*

Country	***Total RAP used in asphalt (Mt)***	***Total asphalt (Mt)***	***Average RAP in asphalt mixes (%)***
Hungary	0.16	4.9	3.2
Germany	9.7	38.0	25.6
France	4.6	35.9	12.8
Austria	0.8	7.3	10.5
US	94.6	432.0	21.9

While many asphalt plants are capable to incorporate 10-15% RAP in Hungary, these limits are not being utilized otherwise 490,000 to 735,000 tonnes of RAP would have been used in 2021. In 2022 an asphalt plant was established in Hungary capable for the addition of RAP up to 60% by using some of the latest technological advancements in hot mix asphalt production. When adding RAP to HMA, some of the economic and environmental benefits are the reduction of primary raw materials, such as crushed stone, bitumen and additives; this also minimizes transport costs. These altogether result in the reduction of the overall carbon footprint of asphalt manufacturing and laying and other greenhouse gases emitted during production.

Within the framework of a research and development project, an asphalt mixing plant was established for the production of asphalt mixtures with a high RAP content. During the project the complex system of large-scale production was established, innovative laboratory testing and mix design was developed and a monitoring system was implemented. Asphalt recycling has several measurable advantages as follow:

- Minimizing the consumption of new bitumen
- Reducing the rate of use of new crushed stone and ground limestone or filler
- Lower energy costs
- Decreasing environmental loading
- Identical asphalt quality if designed and controlled correctly.

Within the framework of the project, RAP stockpile management was considered, such as preparation, processing and storage of processed RAP product and the requirements for the mixing plant were also considered for high level of RAP addition. The primary objective was to produce HMA containing up to 20-50% RAP with a performance equivalent to the virgin HMA, i.e. manufactured without RAP. The level of RAP added to the mix depends on many variables and input parameters, however, within the framework of this paper these details, such as binder blend design and mix design will not be discussed.

This paper focuses on the performance tests carried out on laboratory and plant mixed asphalt mixes with varying levels of RAP and various based binders and the overall full depth asphalt (FDA) pavement performance was predicted through general mechanistic pavement design.

Transitioning from basic and empirical material properties through laboratory evaluation of asphalt mixes to long-term and reliable field performance prediction is the primary objective of pavement design and modelling.

II. PAVEMENT DESIGN TO CONSIDER PERFORMANCE DIFFERENCE – EMPIRICAL AND MECHANISTIC METHODS

Hungary, as a member of the European Union (EU) and the Comité Européen de Normalisation (CEN) - European Committee for Standardization – implements the EN standards on the national level. However, these standards only apply to road construction materials and test methods, and the EU and CEN do not provide harmonised standards for pavement design purposes. The current Hungarian approach in pavement structural design is semi-empirical (mechanistic-empirical).

The selection of input parameters into mechanistic-empirical design is crucial. This approach enables the introduction of innovative materials and technologies, and provides effective pavement structure build-ups. However, the mechanistic-empirical design can only address the structural capacity of the pavement structure and other aspects, such as the plastic deformation or low temperature behaviour also needs to be addressed through other means [5]. The determination of the structural capacity of new or existing pavement structures is one of the most interesting, but most difficult tasks of pavement engineering [6].

Reliable calculation of the allowable loading of a pavement structure considered extremely beneficial from the asset maintenance perspective as it allows allocation of resources and funding in a controlled way and enables maintaining the level of service of the road [7].

The general mechanistic procedure (GMP) is limited to the assessment of load associated distresses and can be used for the assessment of new or existing pavement structures. The method uses computer software to determine the load induced critical strain responses in pavement layers. The critical responses assessed for asphalt materials is the horizontal tensile strain at the bottom of the layer and for subgrade and selected subgrade material it is the vertical compressive strain at the top of the layer [8].

The GMP requires the design moduli for existing pavement layers and the subgrade to be estimated as accurately as possible, for example by back-calculation [9]. This approach has been proven reliable and takes the uncertainties of the pavement design properties into consideration. Currently the Hungarian pavement overlay design method [10] utilises a mechanistic-empirical pavement design system, where a two layered pavement structure is transformed into an equivalent infinite layer using the deflection of the existing pavement structure as primary input and calculates allowable deflection using the general mechanistic procedure (GMP) approach [11, 12]. The method has its constraints, but basically provides a rational tool for pavement engineers. The method provides a solution solely for the asphalt overlay design with limited variability in material performance and unbound granular or concrete overlay is out of the scope for this method.

Originally the calculation of the tolerable deflection was based on the American Association of State Highway and Transportation Officials (AASHO) investigation. Developments in the 1970s indicated that significantly variable pavement structures (unbound granular, full depth asphalt and semi-rigid) have very different tolerable deflections [13]. Based on further data collection and developments in September 1971 the Guidelines for the design of flexible pavement structures (159.215/1971 KPM) were issued (Hungarian abbreviation 'HUMU'), which had been used for more than 20 years after its first publication. By the end of the 1980s the shortcomings of this design method became obvious and, in line with international trends, the decision was made to utilise the pavement technology and testing advancements along with computer supported design and move towards the GMP. After several years of preparation, data collection, training and widespread technical discussions, the new Hungarian pavement design standard was issued for typical pavement structures; this was established in May 1992 and the method was introduced as a legislative requirement in 1994 as 'Dimensioning of asphalt pavements and their overlay' which is still valid today and only minor modifications were made in the last three decades [14].

Unfortunately, significant advancement has not been made in the field of updating this design guideline since its first issue in the early 1990s, therefore the design inputs and methodology are now heavily outdated and cannot be kept up to date to incorporate developments in pavement materials technology. For that reason the benefits of any new pavement materials cannot be shown through a closed loop design as incorporating improved material properties and their transfer functions into the field performance prediction is simply not possible through this existing system. As a result the result of research and development activities cannot be incorporated and their positive life cycle cost benefit cannot be realised. This leads to wasting resources and energy and works against current worldwide trends towards building sustainable transport infrastructures.

Some research and development activity had been carried out in the last decade in order to fill this gap [15], however, no wide spread training and implementation was adopted by the road agencies and asset owners and these developments are significantly under-utilised despite their obvious benefits to the transport sector. There is an international move towards designing asphalt pavements that will last for an indefinite length of time. This concept is known as long life pavement, or perpetual pavement. Improved procedures have been developed for the design of longer life asphalt pavements in a cost effective manner by developing improved procedures for determining asphalt resilience and fatigue performance characterisation. Such approach utilises the flexural modulus master curves of asphalt mixes and makes it possible to reliably determine the design modulus of an asphalt material for any combination of load duration and temperature. It also becomes possible to develop mix specific fatigue models which enables a more direct comparison of mix designs based on expected field performance [16]. This approach requires extensive testing of asphalt mixes at various temperatures and also requires measured or predicted asphalt pavement temperature distributions in various depths. There are other emerging technologies in civil engineering, such as digital image correlation method (DICM) to predict displacements in structures [17].

A number of other countries have introduced sophisticated temperature prediction models, for example the Mechanistic-Empirical Pavement Design Guide (MEPDG) in the US [18]. Interestingly temperature prediction is not required in Hungary as detailed and in-depth pavement temperature data was collected and published widely for the Hungarian climate [19, 20, 21].

In this paper the GMP approach was used, i.e. strains were calculated in the pavement structure and compared with allowable strain levels derived from laboratory fatigue testing conducted at a single temperature. It should be however noted that further refinement of the calculations through the GMP is possible by considering pavement temperature profiles; there is a trend worldwide to utilise such application with the expected benefit to provide more detailed prediction in asphalt pavement long term performance. However, such a calculation requires fatigue testing at multiple temperatures and strain levels and completing such a time consuming test regime was out of scope.

III. PAVEMENT MODELS

The primary objective of the pavement design is to compare the load induced stresses and strains with the capacity of the structure. For example, knowing the geometric dimensions and materials of as simple structure and the load is also known, the strains and stresses can be directly calculated in any cross-section. If the properties of the material is also known the so-called allowable strains and stresses can be established, that is the highest level of repeated strain or stress tolerated by the material before failure occurs. This is the design method for any building structures, bridges or pavement structures (**Fig. 1**).

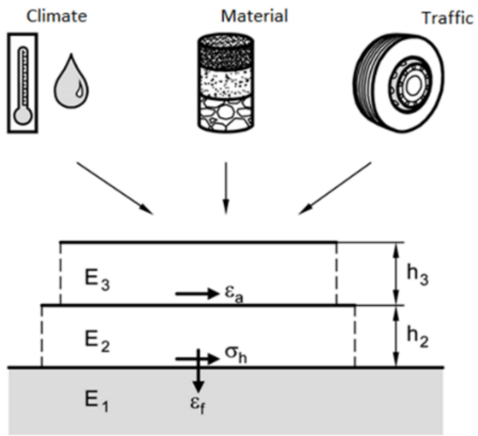

Figure 1. *Simplified road pavement model*

The mechanical behaviour of any layer within the pavement structure is described by the elastic or resilient modulus (E), Poisson's ratio (μ) and layer thickness (h). These three parameters provide the input into the mechanical model of the pavement structure. The load placed on top of the upper pavement layer induces strains, stresses and displacements in the structure and these can be calculated at any internal point of the multilayer system. Then the traffic volume and axle load is estimated and the allowable strains and stresses are determined from the fatigue properties of the relevant pavement layers. This is normally established through advanced and detailed laboratory testing.

By comparing the actual and allowable strains and stresses, the design can be finalised. If the allowable strain or stress is higher than the actual strain or stress, the design is completed. Otherwise further iteration is required in the process, by either increasing the layer thickness(es) or selecting other material type and the new pavement structure has to undergo the above described process again up until the allowable strain or stress is higher than the actual strain or stress. Most design methods are also able to take into account the interlayer bond between layers, which is one of the most important requirements for the construction of a pavement structures. The interlayer bond significantly influences the actual strains and stresses within the pavement structure; this is not only a theoretical assumption, real life experience shows that pavement structures show premature failure if the bond between the asphalt layers is poor, for example due to paving on a dusty surface. Normally full bond is considered in between asphalt layers and slip (no bond) between the lowest asphalt layer and the underlying unbound granular base layer or subgrade.

IV. CALCULATING ACTUAL STRAINS AND STRESSES IN THE PAVEMENT MODEL

Moving forward only strains will be considered in this paper given that asphalt pavements are characterised by strain and not stress due to their visco-elastic nature. Complex and detailed calculations are now supported by powerful computer softwares such as (ALIZE, BISAR, WESLEA, ADtoPave, CIRCLY, etc.). Modern pavement design procedures calculate the following distress in the relevant layers:

- horizontal strain (ε_t) at the bottom of the lowest asphalt layer
- tensile stress (σ_t) at the bottom of hydraulically bound layer
- vertical compressive displacement (ε_v) at the top of the unbound granular base layer or the subgrade.

V. ALLOWABLE STRAINS

The fatigue properties of asphalt mixes can be determined by laboratory fatigue tests. The fatigue test provides the allowable strain versus loading cycles, which is a typical and so called Wöhler curve. From this fatigue function it can be estimated how many loading cycles the material can carry before any cracking develops. It should be noted that the fatigue functions derived from the laboratory tests are not transfer functions. Reliability factors should be utilised to relate a mean laboratory fatigue life to the in-service fatigue life at desired project reliability [22]. It should also be noted that high statistical significance and data fit (R-squared) can be usually achieved by testing 18 specimens [23]. In this study maximum 12 beams were tested due to the large number of mixes and the associated long testing time. **Fig. 2**, **Fig. 3** and **Fig. 4** summarise the fatigue test results, where each point represents a single beam tested, and also provides the earlier mentioned fatigue curve. The allowable strains can be interpolated at 1 million cycles from each curve using regression analysis; the values for the asphalt mixes considered for pavement design are provided in **Table 2**, **Table 3** and **Table 4**.

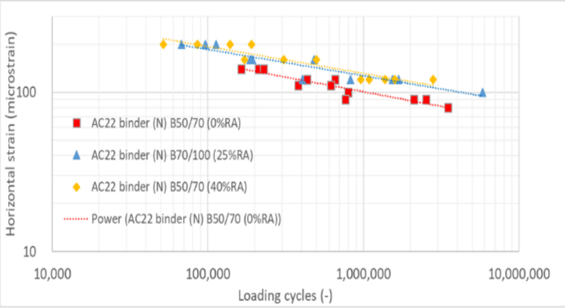

Figure 2. *Fatigue curves of AC22 binder (N) asphalt mix manufactured with plain binder and various RAP contents*

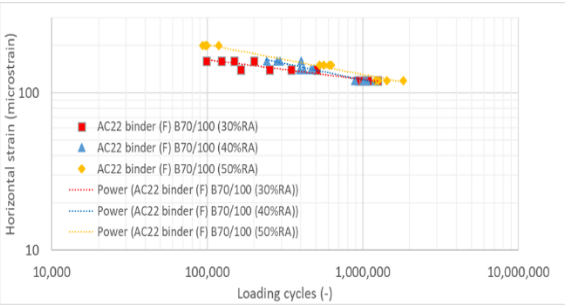

Figure 3. *Fatigue curves of AC22 binder (F) asphalt mix manufactured with plain binder and various RAP contents*

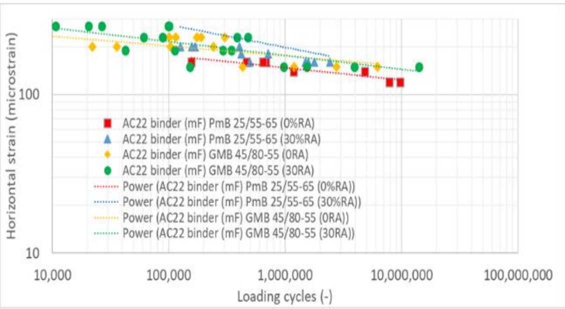

Figure 4. *Fatigue curves of AC22 binder (mF) asphalt mix manufactured with polymer modified and crumb rubber modified binders and various RAP contents*

VI. Pavement models and actual strains in various pavement models

By utilising the principles of the GMP it becomes possible to compare the overall behaviour of various pavement structures built with various asphalt mixes. The primary objective of this paper was to provide performance comparison using asphalt mixes with various RAP contents and binder types.

The performance of different asphalt mixes within a pavement structure can be expressed in terms of allowable equivalent standard axle (ESA) repetition or required total asphalt thickness to meet set number of ESA (usually 1 million).

For the various pavement structures a single wearing course type was utilised. Asphalt wearing courses are functional layers and can be selected from a variety of asphalt types depending on the road type and traffic volume [24]. Since asphalt wearing courses have minimal contribution to the overall bearing capacity, the asphalt pavement and the objective of these calculations are to showcase the impact of various asphalt binder and base layer with varying RAP content, it was decided to model the wearing course by a 40mm thick, 4000 MPa layer without specifying its type. Also, only FDA pavement was considered, where the asphalt intermediate (binder), base and lower base layers were considered identical and their initial total thickness was 300 mm. The lower asphalt base layer is sitting on top of an infinite subgrade with uniform and minimum bearing capacity of 50 MPa. Poisson's ratio for all asphalt mixes was 0.35 and for the subgrade 0.45. For interlayer bond properties full bond was considered in between all asphalt layers and full slip between the lowest asphalt layer and the subgrade.

The main difference between the pavement structures were the various asphalt types with varying RAP content. Extensive laboratory testing provided the material parameters of these asphalt mixes and the variables were as follow:

- Virgin binder type – B (normal bitumen), PmB (polymer modified binder) and GmB (crumb rubber modified binder)
- RA content – varying from 0 to 50%
- Asphalt type – N (for normal traffic volume), F (for high traffic volume) and mF (for extremely high traffic volume)
- Laboratory and plant mixed asphalt mix.

For both laboratory and plant manufactured asphalt mixes RAP was sourced from Zsámbék depot of the Hungarian Main Roads. RAP was split into 0/11 and 11/22 fractions and their grading and binder contents were considered for laboratory batching and plant manufacturing to maintain target grading and binder content identical across all mixes. Softening point of the reclaimed binder was tested as

76°C and complex viscosity as 15 745 Pa.s at 60°C and 1 rad/s.

The first set of pavement structures consisted of an AC22 binder (N) asphalt layers, with varying RAP content. The benchmark mix was made with 0% RAP and the binder was B50/70 usually used for this asphalt mix. Two alternatives were made with 25% RAP and B70/100 binder, considering that the binder blend would provide a binder equivalent to the virgin B50/70, while the other version of mix was made with B50/70 virgin binder and 40% RAP. It was expected that the binder blend in the latter mix will be fairly viscous, more viscous than the benchmark B50/70 binder given that 40% RAP is added. The assumption was true given the modulus value of this asphalt mix exceeded the benchmark mix. The binder blend in the 25% RAP mix with B70/100 binder delivered modulus value comparable to the benchmark mix and it was considered that the binder blend design met its objectives.

With increasing stiffness, the fatigue property is expected to decrease in theory; the test results provided different outcome though. At 1 million load cycles, 131 microstrain was obtained for the 40% RAP mix with B50/70 binder compared to 101 microstrain for the benchmark mix. While this is theoretically not expected, in practice high RAP asphalt mixes tend to show better properties in terms of wheel tracking or moisture sensitivity. This is explained by the composition, i.e. very high proportion of 'pre-coated' aggregates are added through the addition of RAP [25]. For this reason the test results were considered valid and adopted for the calculations (**Table 2**). For all pavement structures analysed in this paper the modulus is characterised by tested resilient modulus value as determined according to EN 12697-26, indirect tensile test on cylindrical samples (IT-CY) [26].

Table 2. *Pavement structures with AC22 binder (N) asphalt mix manufactured with plain binder and various RAP contents, laboratory mixed asphalt*

Structural asphalt	AC22 binder (N)		
RA content	0%	25%	40%
Virgin binder type	50/70	70/100	50/70
Modulus (MPa)	6 600	7 200	10 400
Allowable strain (µs)	101	127	131
Subgrade (MPa)	50		

For the next set of pavement structures an AC22 binder (F) asphalt mix was considered; however, the performance properties were established from test results conducted on bulk samples obtained from large scale plant manufacturing process. The asphalt mix was manufactured with RAP contents of 30-40-50% while the virgin binder was maintained as B70/100. As expected, the modulus value increased with the addition of more RAP as the binder blend became increasingly viscous. Similarly to the test properties showed in **Table 2**, better fatigue results were obtained for the 50% RAP mix when compared to the 30% RAP mix despite the binder blend was more viscous which also transpired in the modulus results. The reasons behind this observations are discussed above and the pavement inputs are summarised in **Table 3**.

Table 3. *Pavement structures with AC22 binder (F) asphalt mix manufactured with plain binder and various RAP contents, plant mixed asphalt*

Structural asphalt	AC22 binder (F)		
RA content	30%	40%	50%
Virgin binder type	70/100	70/100	70/100
Modulus (MPa)	12 700	14 700	15 900
Allowable strain (µs)	122	121	131
Subgrade (MPa)	50		

For the last set of pavement structures an AC22 binder (mF) asphalt mix was considered with PmB and GmB binders. Both mixes were tested with 0% RAP for benchmarking and with the addition of 30% RAP. It was expected that when adding 30% RAP the original PmB and GmB properties cannot be maintained as the binder blend is heavily influenced by the RAP binder and the PmB and GmB properties are somehow 'diluted' (**Table 4**).

Asphalt mixes within the type (N, F and mF) were mixed or manufactured in a manner that combined aggregate grading, binder content and volumetric properties were targeted to be identical in order to close out the impact of volumetric variables. Binder blends were designed using sophisticated and controlled methods, however, these details are

Table 4. *Pavement structures with AC22 binder (mF) asphalt mix manufactured with polymer modified and crumb rubber modified binder and various RAP contents, laboratory mixed asphalt*

Structural asphalt	AC22 binder (mF)			
RA content	0%	30%	0%	30%
Virgin binder type	PmB 25/55-65		GmB 45/80-55	
Modulus (MPa)	6 300	7 200	5 500	7 400
Allowable strain (µs)	148	169	175	177
Subgrade (MPa)	50			

Table 5. *Actual strain calculated at the bottom of the lower asphalt base layer*

Asphalt layer	RA content (%)	Allowable strain (µs)	Actual strain (µs)
AC22 binder (N)	0	101	79
	25	127	73
	40	131	51
AC22 binder (F)	30	122	42
	40	121	37
	50	131	34
AC22 binder (mF)	0	148	82
	30	169	73
	0	175	93
	30	177	71

Table 6. *Thickness requirement to meet allowable strain levels - pavement structures with equivalent bearing capacity*

Asphalt layer	RA content (%)	Thickness at 1million cycles (mm)	Thickness difference compared to benchmark (mm)
AC22 binder (N)	0	260	0
	25	220	40
	40	180	80
AC22 binder (F)	30	165	0
	40	170	-5
	50	160	5
AC22 binder (mF)	0	220	0
	30	190	30
	0	210	0
	30	180	30

discussed elsewhere [27, 28]. The actual strains within the relevant pavement structure were calculated using the WESLEA software and summarised in **Table 5**.

As per the design methodology the actual strain should be less than the allowable strain as expressed by equation (1), where $\varepsilon_t(N)$ is interpolated from the laboratory fatigue curve at 1 million ESA, as explained earlier.

$$\varepsilon_t \leq \varepsilon_t(N) \qquad (1)$$

Based on the calculations, all pavement structures met the design criteria as the allowable strain was higher than the actual strain. All of these pavement structures could be utilised as they would be performing till the end of their design life. While these asphalt mixes have vastly different performance properties, they would be all considered equivalent in the currently adopted pavement design system.

In order to showcase the performance difference in between the various pavement structures and also highlight the benefits of the GMP, the thickness of the combined structural asphalt layers was varied until the actual strain was equal to the allowable strain. In this case all pavement structures were identical in terms of their structural capacity. In **Table 6** the thicknesses are summarised along with the thickness differences compared to the pavement structures with baseline (benchmark) mixes; these are highlighted in grey. For a better overview **Fig. 5**, **Fig. 6** and **Fig. 7** visualise the outcomes of these calculations.

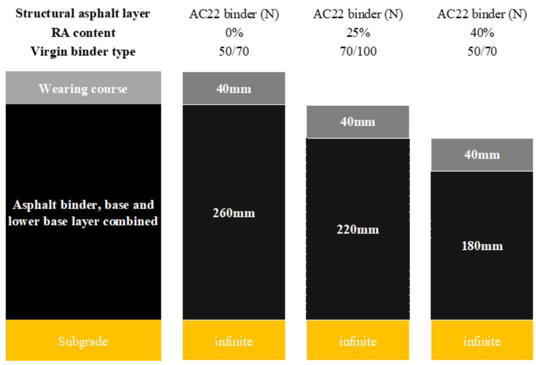

Figure 5. *Summary of total binder, base and lower base asphalt layer thickness for pavement structures with AC22 binder (N) asphalt mix and equivalent bearing capacity*

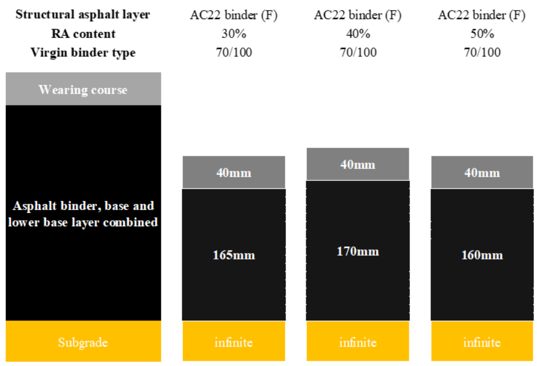

Figure 6. *Summary of total binder, base and lower base asphalt layer thickness for pavement structures with AC22 binder (F) asphalt mix and equivalent bearing capacity*

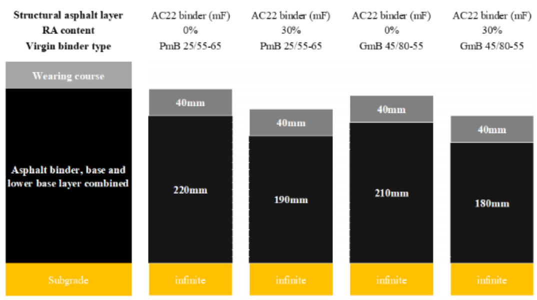

Figure 7. *Summary of total binder, base and lower base asphalt layer thickness for pavement structures with AC22 binder (mF) asphalt mix and equivalent bearing capacity*

VII. Conclusions

Considering a cost-benefit approach using the performance assessment of full depth asphalt pavements with high RAP content, there is an economic and in-situ performance benefit. Further positive impact can be achieved by the addition of warm mix additives, which positively impacts the performance and the carbon footprint due to lower production temperatures [29]. The benefits can be realised on high volume roads, such as motorway, due to their high material volume requirements. The associated risk with using high RAP content asphalt mixes, as shown in this paper, is not different to the application of virgin mixes, i.e. mixes manufactured without RAP. Incorporating high RAP content into low volume roads, such as residential streets certainly brings an economic benefit and the associated performance risk is even lower considering the lower traffic volume. The binder blend design is however critical for both high and low volume roads. The latter tends to deteriorate due to environmental loading and not traffic loading. For example over-stiffening a mix with the addition of high RAP and not carefully adjusting the binder blend in the mix by the appropriate selection of the virgin binder may lead to premature distress of the asphalt pavement due to diurnal temperature variations and associated thermal cracking.

The outcomes of this paper disproved the common perception that is high RAP content asphalt mix show substandard performance. The analysis performed in this paper found that asphalt mixes with high RAP content have high performance and present low risk for in-situ conditions, subject to correct mix design methodology, including binder blend characterisation, appropriate RAP management and suitable asphalt plant capability for mass production.

The incorporation of high RAP content asphalt mixes into pavement structures results in responsible utilisation of resources and energy and lines up with worldwide trends towards building sustainable transport infrastructures.

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AUTHOR CONTRIBUTIONS

Cs. Toth: Conceptualization, laboratory testing, review.

L. Petho: Mix design, analysis, writing and editing.

Sz. Rosta: Production control, testing and analysis.

P. Primusz: Pavement modelling.

Disclosure Statement

The authors have no known conflict of interest to declare.

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