EAPA

High-performance Asphalt Pavements – adapting for future road networks

March 2022

Published by the European Asphalt Pavement Association
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The present document may be cited as:
European Asphalt Pavement Association (EAPA). High-performance Asphalt Pavements – adapting for future road networks. EAPA Technical Review (2021) 22 pages.
https://eapa.org/download/12741/

Abstract

Increases in the European road freight transport, vehicles weight, tyres pressure and frequency of extreme climatic events are deteriorating the European road network at an anomalously fast rate, bringing it close to the end of its service life and requiring more frequent maintenance operations. In this unfavourable scenario, road transport is also nowadays experiencing one of the greatest revolutions of its history, with the arrival of new users, such as the autonomous, electric and high-capacity vehicles, which will help mankind to fight Climate Change and increase road safety. However, all these are vehicles with enhanced road requirements (VERR) might need pavement solutions that traditionally were only used in particular applications. The present paper gathers the main technologies and design criteria, which Asphalt Industry developed over the last years to support this type of traffic, while ensuring adequate durability and safety in our roads. Asphalt Sector is completely prepared and has capacity to give support to the traffic of new vehicles with enhanced road requirements, as well as to adapt the European road network wherever necessary.

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1. Introduction

In order to give and answer to the current climate and environmental-related challenges, the European Commission included in The European Green Deal [1] the new growth strategy that aims to transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy where there are no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use. For this, European policies forecast a future transport system that is resilient, resource-efficient, climate- and environmentally-friendly, safe and seamless for the benefit of all citizens, the economy and society.

In this sense, the bad state of road surfaces leads to higher fuel/electricity consumption, vehicles and road maintenance costs, emissions and delays in travel time. Therefore, in order to meet EU requirements, roads must be durable and require minimum maintenance operations and traffic disruptions. All this, while ensuring that sustainable materials, which guarantee the reusing/recycling at the end of the road's service life, are used.

However, numerous emerging factors are hindering these objectives. For example, extreme events, such as floods or record-breaking temperatures, are more and more frequent every year due to Climate Change. Hence, over the last decades, a great deal of European surface transport infrastructures has experienced an anomalously fast rate of deterioration, bringing them close to the end of their service life.

Moreover, the traffic demands keep increasing. According to Eurostat [2], the road freight transport in the EU-28 countries increased by 23.7% from the begining of 2015 to the begining of 2021 (figure 1). With the exception of the years of EU economic crisis and the second quarter of 2020 due to the Covid pandemic, this increasing trend has been present for decades.

In this unfavourable scenario, road transport is also nowadays experiencing one of the greatest revolutions of its history, with the arrival of new types of vehicles, such as the autonomous, electric and high-capacity vehicles. Such vehicles, expected to be among the main tools of humanity to reduce transport emissions (figure 2) and increase road safety, might also worsen the distress produced on our road infrastructures accelerating the road pavement deterioration over time, requiring specific designs and solutions, when a significant number of these is expected on a given road. For this reason, they can be named Vehicles with Enhanced Road Requirements (VERRs).

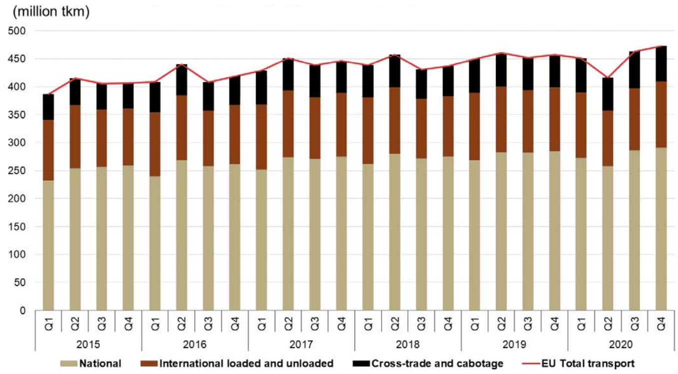


Figure 1. Quarterly rad freight transport by type of transport, EU-28, 2015-2020 [2]

The main impacts of these are:

1. Heavy vehicles. Improvements in transport efficiency and technical developments in the automotive industry have also contributed to increase axle loading as well as higher tyre pressures. Greater use of high pressure super single tyres is getting more and more usual, while the total weight of trucks keeps growing. This has potential to increase rutting and fatigue cracking.

2. Electric vehicles following a catenary (overhead system) or a conductive rail embedded in the pavement (in-road system) to charge batteries on-the-fly tend to "hit" always the same spots of the road cross section. This produces a concentration of stresses in these spots, reducing service life.

3. High-capacity vehicles (HCV) are vehicles especially designed to carry more freight than a standard vehicle. As it can be seen in Figure 2, depending on the configuration and usage, these vehicles have potential to reduce carbon emissions at the individual vehicle level in the range of 15%-40% [3]. However, these vehicles will need to increase either the axle load or the number of axles, potentially leading to either higher pavement stresses or shorter recovering time between loads, increasing fatigue and/or rutting in the pavement.

4. Autonomous vehicles. A digital evolution of previous point comes hand in hand with

the development of autonomous vehicles and the formation of groups of vehicles driving in line, at the same speed and at a very reduced distances between them (system also known as Platooning). This system, especially beneficial for the aerodynamics of large vehicles and, consequently, for the reduction of their fuel/electricity consumption, significantly shorten the recovering time elapsed between consecutive loads on the same spot of the road cross section. This phenomenon might produce, again, the premature rutting and/or fatigue damage of the road. In addition, similarly to the case of electric vehicles, these will tend to self-position in the centre of the lane, which might produce the premature deterioration of the overloaded areas, in the form of rutting and/or fatigue cracks.

As approximately 90% of European road network is made of asphalt, the sector has already reacted developing high-performance asphalt solutions especially designed to deliver safe and durable roads in the above-mentioned scenario. This document provides an overview of such solutions for high-performance pavements, as well as design information, with the aim of promoting their correct use among Road Authorities and the rest of involved stakeholders.

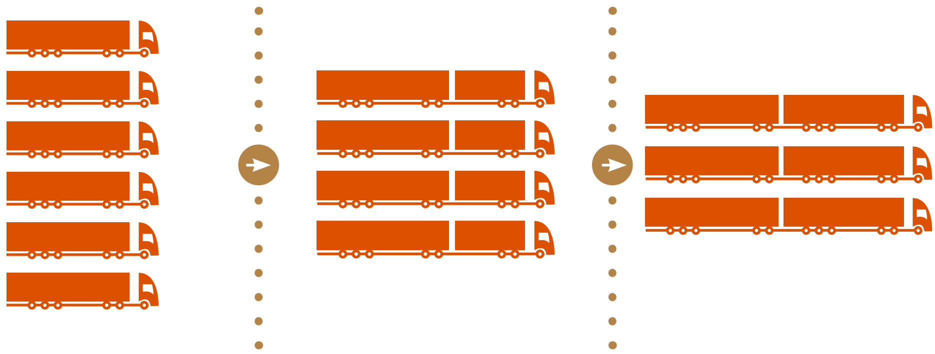
2. Higher requirements for the future road network

The main sources of damage, which are normally taken into account when designing a conventional pavement are: repeated tensile stress/strain at the bottom of asphalt layers (leading to fatigue cracks), repeated compressive strain at the top of the granular sub-base (leading to permanent deformations), rutting (permanent deformation due to compaction by the traffic or plastic and viscous deformation caused by shearing stresses) and polishing/ravelling of the wearing course.

For these actions, it is common that the only mechanical input considered is the axle load. As the structural impact of a light vehicle differs from the impact of a heavy vehicle, the concept of the "Equivalent number of Standard Axles" (called frequently also Equivalent Single Axle Load or ESAL's) has been developed: the impact of each axle of vehicles passing is equal to the impact of an equivalent number of standard axles (where the loading of the standard axle generally is 80kN, 100kN or 130kN, depending on the country).

For structural design purposes the equivalent number of standard axles is usually calculated from actual measured axle loads and numbers by the Fourth Power Law: "the damaging effect of an axle load is the fourth power of the relative axle load compared to the standard load" (even if some countries as France or Czech Republic use the 5th power law). In other words, the number of applications of a standard axle load (in kN) that produces the same damage than a given load, L (also in kN) is:

$$N_{equivalent} = \left(\frac{L}{ESAL}\right)^4$$



Vehicles (and drivers)	**6**	**4**	**3**
Vehicle length	16.5m	25.25 m	32 m
Load per vehicle	100 m^3	150 m^3	200 m^3
Fuel consumption	3.5 ml/m^{3km}	3 ml/m^{3km}	2.5 ml/m^{3km}
CO2 emissions	100%	85% **= -15%**	73% **= -27%**
Road use	499 m	368 m	296 m

Figure 2. Transportation of 600 m^3 of volume limited goods with the same density (150 kg/m^3) [4]

This means for example that the damaging effect of 1 axle load passage of 100 kN is equivalent to the damaging effect of:

- 0.4 passages of an axle load of 130 kN (one 130 kN-axle equals 2.5 100 kN-axles);
- 0.6 passages of an axle load of 115 kN (general maximum EU permitted axle load);
- 2.4 passages of an axle load of 80 kN;
- 162 passages of an axle load of 28 kN;
- 160,000 passages of an axle load of 5 kN (average private car).

From this list it becomes clear that for the structural design of an asphalt pavement, in general, only industrial vehicles are relevant.

For calculations of permanent deformation, another rule should be followed, e.g. as given in the Shell Pavement Design Manual (SPDM) [5]. In the permanent deformation model of the SPDM the damaging effect of a wheel passage is related to the (1/q)-power, where q is the slope of the log S_{mix} - log S_{bit} curve. This means that the effects of increasing wheel loads develop between the fifth and the tenth power, depending on the asphalt mixture type.

For typical values, where (1/q) = 7, the damaging effect from one application of a 100kN axle load in terms of deformation is equivalent to the following:

- 0.2 passages of an axle load of 130 kN (one 130 kN-axle equals five 100 kN-axles);
- 0.4 passages of an axle load of 115 kN (general maximum EU-axle load);
- 4.8 passages of an axle load of 80 kN;
- 7 400 passages of an axle load of 28 kN;
- 1,300,000,000 passages of an axle load of 5 ken (average private car).

So, in relation to permanent deformation, the effects of low axle loads/tyre pressures can be discounted even earlier than is the case in structural design, whereas the effects of overloading/higher pressures are even more marked.

In addition, earlier deformations can also appear due to the high summer temperatures. These temperatures have only limited impact on the fatigue resistance, but it can be very significant on permanent deformations.

Regarding the speed of loads, pavements carrying slow-moving heavy traffic will be under-designed because the stiffness decreases with the loading speed [6]. In this sense, numerous design recommendations can be found across Europe. For example, the publication "The London Bus Lane and Bus Stop Construction Guidance" states that where traffic is slow moving and/or channelized, this traffic load has to be increased by a factor of 3 [7]. There are other specifications, such as the Australian, which take into account the vehicle speed by giving different stiffness values for the asphalt layer depending on the traffic speed. Other studies have shown the direct relationship between load frequency and fatigue life [8]. Some of them [9] suggest that damage by permanent deformation could increase by a factor of 70 when the heavy traffic moves at 10-15 km/h, compared to the damage at 50 km/h, whereas, in the case of fatigue, damage increases by a factor of 4.

Despite previous considerations, it might look like, as far as axle loads are not increased, which can be obtained by increasing the number of axles, and the same limiting/functional speed applies, VERRs

Table 1. Presumptive values for elastic characterisation of asphalt mixtures

Asphalt mix type	Binder type	Volume of binder %	Asphalt modulus at heavy vehicle operating speed MPa 10 km/h	30 km/h	50 km/h	80 km/h
OG10	A5S	N/A	800	800	800	800
OG14	A5S	N/A	800	800	800	800
SM14	A5S	13.0	1000[a] (600)	1000a (900)	1100	1300
DG10	C320	11.5	1000[a] (900)	1300	1600	1900
DG10	A5S	11.5	1000[a] (600)	1000a (800)	1000	1200

From State of Queensland (2013), Table Q6.5

[a] Indicated values have been limited to a value of 1000 MPa

would just affect the road in the same way than conventional vehicles. However, studies in France [10], where strain measurements were obtained in a pavement under the action of different axle configurations, showed that tridem configuration with single wheels (42.5 kN per wheel) produced higher tensile strains, and is therefore more aggressive than single axles with dual wheels loaded at 65 kN.

In addition, VERRs described above have potential to produce an accelerated pavement damage, not only because they may have higher axle loads but because such loads are applied with lower scattering and shorter recovering time (Figure 3).

- Fatigue: If the axle load of VERRs does not increase, fatigue damage should not be greater than that produced by conventional vehicles and the design based on the number of equivalent axle loads that the pavement will resist should be suitable. Nevertheless, if the scattering of loads position reduces and all the wheels hit the cross section on the same spots, the overall fatigue damage of the road might reduce but sharply increase on such specific spots. Consequently, premature maintenance would be needed.
- Rutting: As asphalt is a visco-elasto-plastic material, it needs a certain period of time to recover the deformations produced by a given load. If a series of loads are applied with a recovering time shorter than needed, new deformations would be accumulated before the previous were recovered. Consequently, the deformation distress on the cross section increases and rutting processes accelerate.
- Polishing and ravelling: if the axle loads do not increase, these types of damage should remain the same than with conventional vehicles. However, as the damage is induced by lateral forces, it can be increased under the action of multiple axles. Hence, the configuration of the vehicle (length between axles, articulations, etc.) and the geometry of the road will affect the durability of the surface.

For these reasons, the deterioration produced by VERRs will depend on their configuration (number of axles, length, speed, allowed scattering, etc.), as well as the pavement structure and design (stiffness, elastic recovery, rutting resistance, etc.), and it should be assessed in comparison to a standard vehicle. Hence, vehicles may be first classified according to such characteristics and consequent aggressiveness [11] and then the pavement must be designed based on the number and type of vehicles expected to pass by.

When such combination of factors has potential to produce the premature failure of the pavement, high-performance solutions must be adopted. Hence, over the coming years it might be necessary to, step by step, shift our pavement designs towards heavy-duty pavement solutions that traditionally were mainly used in:

- Roads, which carry more than 1.2 x 106 standard axle loads of 100 kN per year (approx. 5000 SAL 100kN/lane/day or 3000 - 5000 HGV/HGV-lane/day). These pavements carrying very high traffic volumes will have 10 to 20% commercial vehicles.
- Container terminals, airfields, industrial sites, parking areas, which carry static loads of over approximately 1 N/mm2 etc.;
- Bus lanes, stacking lanes, creep lanes etc. with more than 1.2 x105 standard axle loads of 100 kN per year (approx. 500 SAL 100kN/HGV lane/day).

It must be also added that, like in the case of embedded tram rails in urban roads, for the specific case of electric vehicles being charged by energy supplying systems embedded into the pavement (e.g. conductive rails or induction coils), differences between the stiffness of asphalt and steel may produce differential settlements between both elements, producing cracking around the rail. In addition, if the conductive systems are not properly designed to dissipate the heat they may produce, they could lead to the premature ageing of the binder and softening of the embedding asphalt mix.

Asphalt Industry has developed over the last years, specific solutions for all the described situations, as it will be described in the next Section. Therefore, **Asphalt Sector is completely prepared and has capacity to adapt the road network to the new challenges of VERRs.**

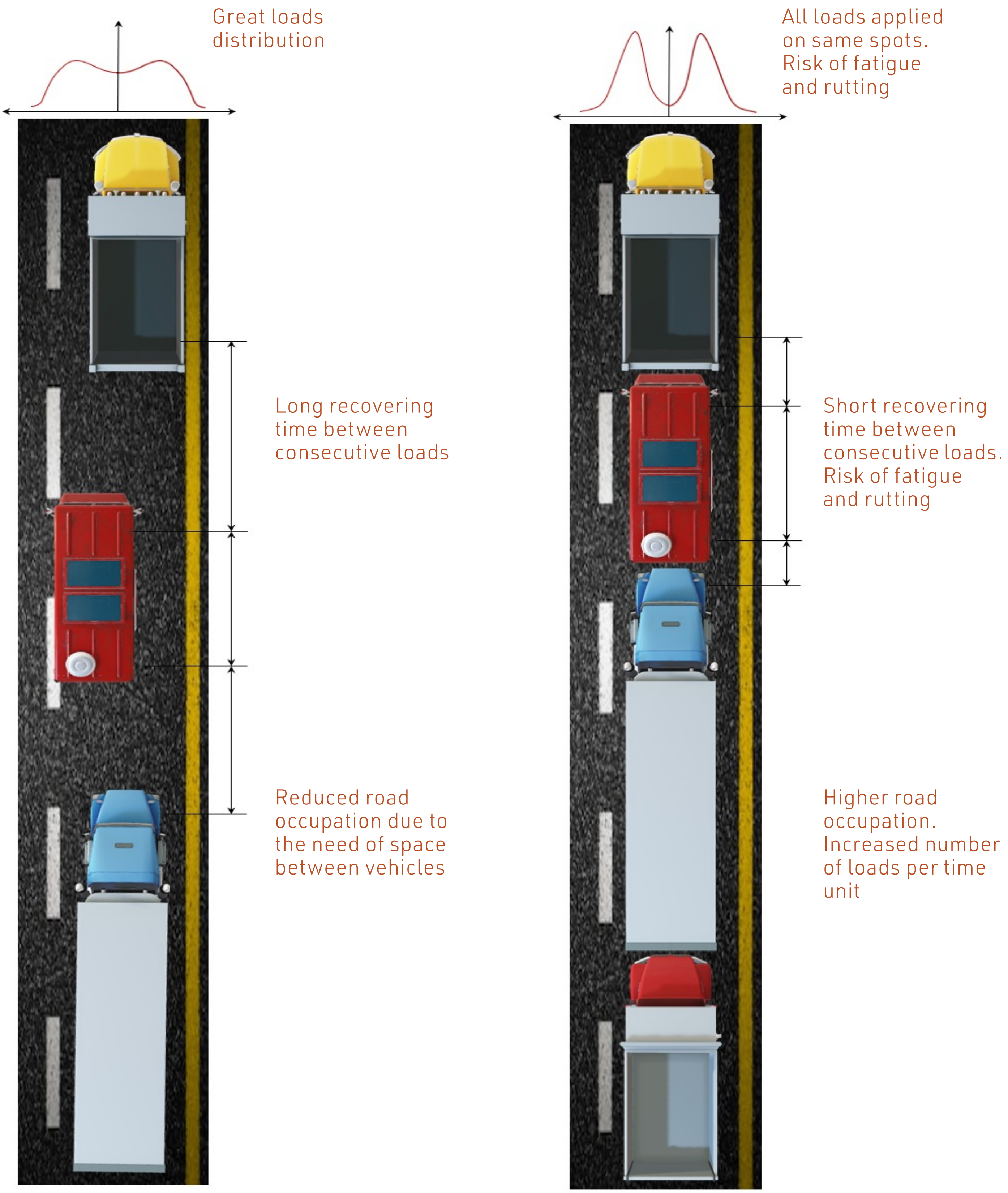


Figure 3. Differences in load application between current vehicles (left) and electric and autonomous vehicles (right)

3. Solutions of Asphalt Industry for vehicles with enhanced road requirements

3.1 Introduction

More than 90% of the European road network is made of flexible pavements consisting in a series of overlapping layers, where the most superficial are made of asphalt and that underneath are usually made of unbound granular materials (Figure 4).

In conventional pavements, asphalt layers are normally three, called from top to bottom: surface course, binder course and base course. In order to obtain satisfactory bearing capacity and durability, it is important to ensure a good bond and interlock between adjacent asphalt layers, as well as between these and the granular layers underneath.

Surface courses are designed to provide an even profile for the comfort of the user, while providing enough texture to ensure minimum and safe skid resistance. Depending on local conditions, functional characteristics, such as skid resistance, noise reduction and durability, are often required for wearing courses. In some cases, rapid drainage of surface water is desired while in other cases, the wearing course should be impermeable in order to keep water out of the pavement structure.

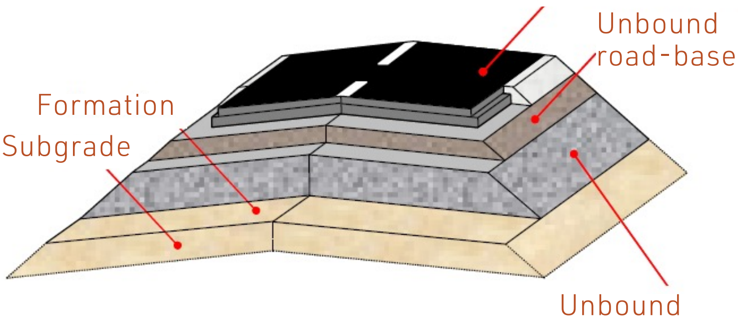


Figure 4. Schematic illustration of flexible pavement structure

Binder courses are designed to withstand the highest shear stresses that occur about 50 – 70 mm below the asphalt surface. The binder course is therefore placed between the surface course and base course to reduce rutting by combining qualities of stability and durability. Stability can be achieved by enough stone-on-stone contact by appropriate gradation curve and stiff and/or modified binders.

The base course is perhaps the most important structural layer of the pavement, which is intended to effectively distribute traffic and environmental loading in such a way that underlying unbound layers are not exposed to excessive stresses and strains. This often implies comparatively high stiffness of the base course. Next to this the base course should also show adequate fatigue resistance. For these reasons, this layer is usually the thickest (sometimes exceeding 200 mm).

When the traffic distresses become a challenge (heavy axle loads, VERRs, etc.) each of the previous layers need to be optimised. With this aim, Asphalt Industry has developed over the past years a series of materials and construction techniques, which protect the road against distresses, such as bottom-up fatigue, rutting in the unbound layers or frost heave. Consequently, service life of pavements and maintenance intervals are extended.

Some of these solutions have been developed from old concepts, such as full-depth asphalt pavements, consisting of relatively thick bitumen-bound layers directly constructed on the sub-grade or placed on relatively thin granular base courses. In the past, experiences in the UK also showed that when asphalt layers exceed the minimum asphalt depth of 180 mm [6], these pavements showed no evidence of structural failure over the entire service life. Nevertheless, today the traffic is more intense and aggressive. This means that, although top-down cracking is more frequent, "classic" bottom-up fatigue can still happen. As stated in pavement design methods of countries, such as France, Germany, Austria or Czech Republic, in order to avoid bottom-up fatigue, it is necessary to select thicker asphalt layers (160 to 300 mm), where thickness is determined for the total forecasted traffic in the design period.

With all these considerations, it can be concluded that when a flexible pavement is well designed and constructed, only superficial distress mechanisms develop, which significantly facilitates road maintenance [12-13].

3.2 High-performance surface courses

The highest stability and durability in surface courses are obtained when Stone Mastic Asphalt

(SMA) is used [14]. This type of asphalt mix is composed of a strong coarse aggregate skeleton, which gives the high stability and resistance to permanent deformation, and stiff and elastic mastic which provides an outstanding durability. In order to obtain a mastic with such characteristics, high amounts of binder (commonly polymer modified) can be mixed with binder drainage inhibitors (e.g. cellulose or specific organic materials) and a high amount of filler. The resulting combination of coarse skeleton and mastic in a mix with low voids content (2%-4%) makes that phenomena, such as stripping, cracking (either thermal or produced by traffic) and ravelling are rare, to the point that some SMA surface layers have resisted for more than 30 years without maintenance.

Still, it must be emphasised that, in order to obtain such a high level of performance when SMA is applied in very thin layers, it will be also necessary that the bearing capacity (the resistance to permanent deformation) of the bound and unbound base and binder courses are sufficiently high.

To prevent binder drainage caused by the high binder content in relation to the surface of the aggregate, especially during storage, transport and laying, binder drainage inhibitors can be added. Most of them are only active during the construction stage but some proprietary inhibitors have been found to also give improved resistance to permanent deformation at higher temperatures, reduced ageing of the bitumen, increased fatigue strength and further increases in durability giving longer service life.

The skid resistance of these mixes is normally very high and can be optimised based on two factors: the selection of the type of aggregates and the surface texture design. Aggregates with an adequate polishing coefficient must always be used, which is defined as such in different national regulations. The surface texture can be modified by changing the size of the aggregate and the degree of filling of the voids with mastic. In general, for conventional mixes with "positive" texture and as long as the surface voids are not oversaturated with mastic, the greater the size of the aggregate, the greater the grip. However, mixes, such a SMA have "negative" texture (Figure 5). In these cases, the use of smaller aggregate sizes can contribute to increase the number of contact points between tyre and road surface and consequently, to improve the skid resistance. For this reason, the global trend is to use smaller aggregate fractions e.g. SMA 10 instead of SMA 14 in the UK, SMA 8 instead of SMA 11 in Germany, etc.

Moreover, as the thickness of the binder film on the surface is higher, skid resistance during the first few weeks might slightly reduce. For this reason, in some countries, the application of a simple layer of fine aggregate (1-3 mm) is common during the last compaction passes.

In addition, the great surface texture allows that more rainwater is stored in the surface reducing splash and spray. It also reduces glare at night from the reflection of lights of oncoming vehicles, increasing visibility of road markings and reduces significantly traffic noise.

In order to further reduce traffic noise, some countries often use porous asphalt (PA) in surface courses. In this case, its thickness depends on the speed and percentage of heavy traffic, which tend to produce most of the low-frequency rolling noise. Hence, thickness of the layer must be increased accordingly to the expected percentage of heavy vehicles using the road, especially at night hours. Experiences in German motorways used a thickness of 5.0 cm for 45% of heavy traffic at night under a speed limit of 120 km/h, showing that such solution was also effective for a speed range from

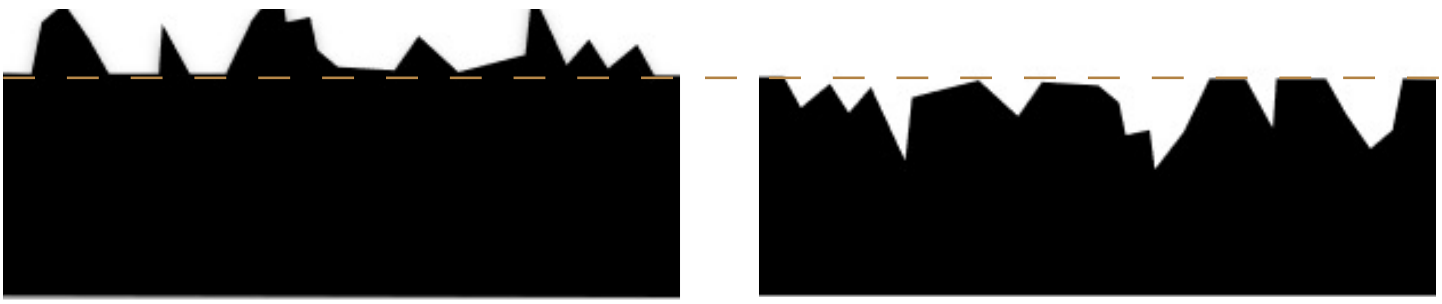


Figure 5. Difference between the positive texture of mixes (left) and the negative texture of mixes, such as SMA (right)

80 km/h and with a constant or smaller percentage of heavy vehicles. In this solution, extra 0.5 cm was added to allow the formation of a clogging area by dirt and ascending bitumen from the waterproof layer placed immediately underneath.

3.3 High-performance binder courses

Depending on the structure of the pavement, high-performance binder courses can be also obtained by replacing conventional asphalt mixtures, e.g., asphalt concrete by SMA. This has been extensively done in countries, such as Germany, where the specification for upgraded binder course mixes is being developed in this direction.

Thanks to the great internal friction mechanism of SMA, this solution is especially relevant for asphalt pavements designed to distribute and resist loads through the use of asphalt layers with high stiffness and reduced strain.

In addition, to the excellent mechanical properties, SMA binder layers provide great waterproofing effect, which protects the layers underneath from the rainwater. This is especially relevant when the surface course is made of a permeable material, such as porous asphalt.
For all these reasons, the experience has shown that the use of SMA binder courses can significantly improve the overall performance and durability of certain pavement designs.

3.4 High Modulus Base Courses

One of the significant failure criteria for analytical pavement design models is fatigue cracking from the bottom of the pavement. Therefore, increases in the resistance to fatigue cracking of the bituminous material applied there would be of interest. This benefit can be obtained by increasing the standard "optimum" binder content of about 0,5 % [15-17] (so called rich bottom layer – RBL). This technology is used in some countries. In other countries such as Czech Republic, it will be included soon in the new National Standard for special asphalt mixes.

RBL is used as a base layer only in cases when there is a sufficient thickness of asphalt layers above. The increased binder content does not necessarily lead to the decrease of stiffness, as the void content of RBL mix is lower. Moreover, if modified bitumen is used, fatigue resistance can be further increased. However, especial care must be taken during design and execution, as merely increasing the binder content could reduce the resistance to permanent deformation, which as explained before, might be one of the weakest points for the case of certain VERRs, which apply a series of consecutive loads on the same spot and with short recovering time in between (e.g. platooning or heavy-duty vehicles with many axles).

A different solution are the High Modulus Base Courses, created in France and also so-called "Énrobes avec Module Élevé". They are bituminous layers with a balanced combination of closed structure and hard bitumen, which increase the mix stiffness and resistance to rutting, and an increased bitumen content, which ensure workability, water resistance and fatigue durability.

Traditionally used as base courses in long-life roads, with design periods of 40 or 50 years, they might become more and more frequent, as long as heavier traffic and VERRs circulate throughout our road networks.

3.5 New concepts for pavement structures

Over the last years, new roads have been built with a pavement structure different from the conventional one explained above, with the aim of optimising each asphalt layer for the main type of distress they have to resist at that depth. Thus, a balance between stiffness and fatigue resistance was obtained.

An example of this is a system used in Poland, based on the concept of "Perpetual Pavements", and consisting on a SMA wearing coarse followed by a thick high-modulus binder course and a 75-100 mm anti-fatigue base layer made of asphalt concrete with highly polymer-modified bitumen PMB 45/80-70 (Figure 6). In this structure, the high-modulus layer resists the maximum compression and shear stress, while the maximum tensile fatigue, happening at the bottom of asphalt package, is resisted by the anti-fatigue layer, especially designed for it.

A further evolution of previous points consists of substituting the traditional structure (surface-binder-base course) by a triple SMA layer made with highly polymer-modified bitumens (e.g., PMB 45/80-80 and 25/55-80), which have significant increases in softening point, elastic recovery and consequent resistance to fatigue and permanent deformations. Hence, this kind of solution can be relevant for very special traffic areas, such as container terminals, bus lanes or terminals, etc. Triple SMAs have been used in countries, such as Sweden, for many years. A recent example can be also found in the service roads at a refinery in the city of Gdansk (Poland), where the pavement was designed to resist super-heavy and super-slow traffic (<20 km/h) (Figure 7).

In this system, the layer immediately under the wearing course (90 mm binder course of SMA 22 PmB 25/55-80) is the stiffest and thickest, as it is there where the maximum compression and shear stress will take place. On the contrary, the layer below (60 mm highly modified SMA anti-fatigue base course layer (SMA 16 PmB 45/80-80) was designed to be elastic, as it will need to resist the greatest tensile fatigue stress. The top wearing course was an SMA, which offered great durability, skid resistance and recyclability.

Laboratory rheology tests also showed that this solution provided lower stiffness at low temperatures, while higher stiffness at high temperatures. In addition, also the stiffness at low frequencies resulted better, being an ideal solution for the heavy and slow traffic that this pavement had to support. Further economic costs assessment also showed that the costs were lower than with the equivalent alternative in cement concrete.

3.6 Advanced pavement execution

in order to ensure maximum performance in pavements subjected to high-stress conditions, it is crucial not only to use of the best techniques for every stage of the supply chain but to optimise the logistics and coordination between all the stakeholders involved in road construction (mixing plant, transportation, paving, compaction, etc.).

Unlike other materials, hot mix asphalt always required such coordination between stakeholders to minimise the temperature losses during the process. This collaboration, forged over the last decades, allowed the implementation of advanced manufacturing techniques, such as the so-called "compact asphalt technique", which consists of two consecutive layers placed "hot on hot" and compacted together, producing an intensive bonding between them due to an enhanced adhesion and interlocking. This technique reduces

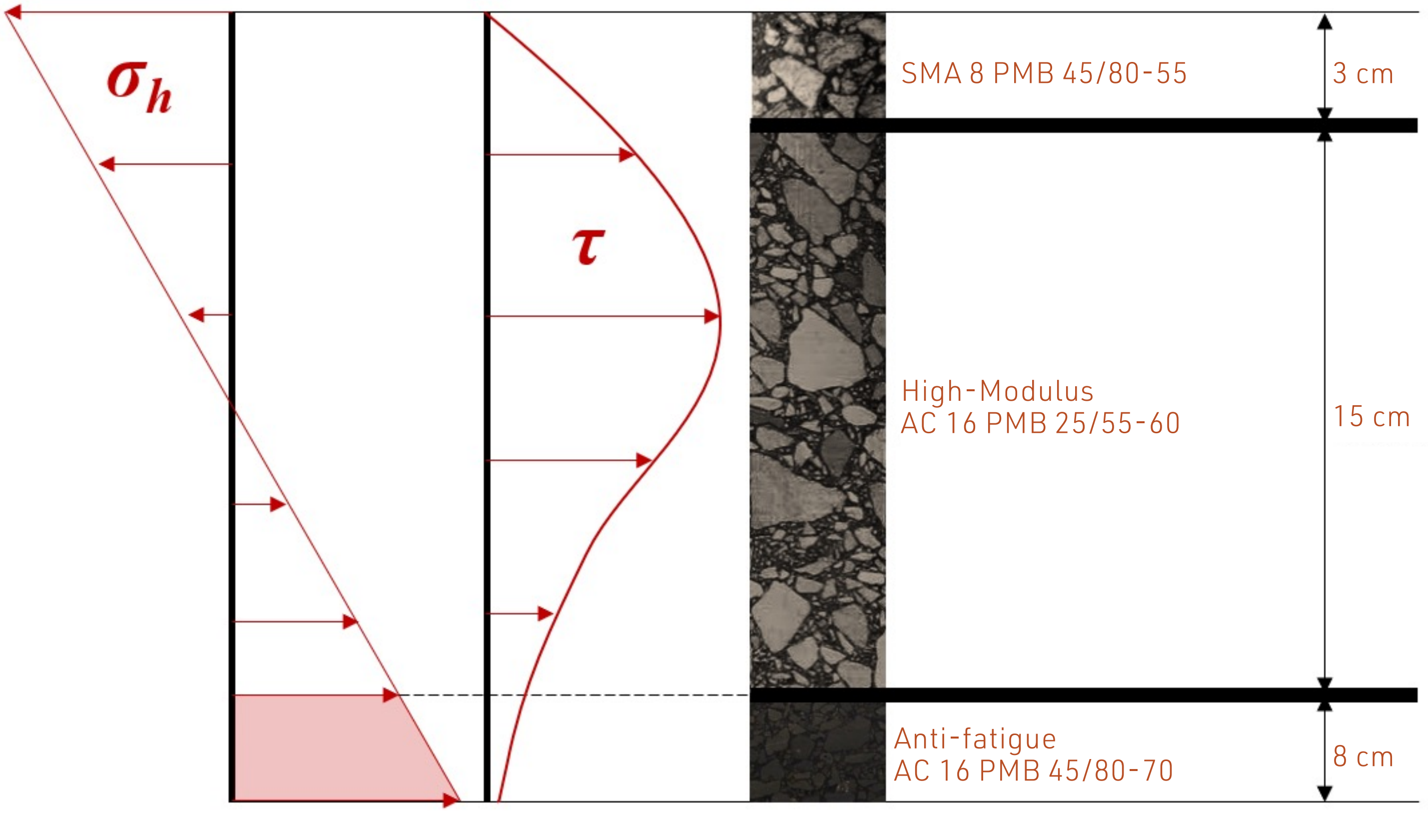


Figure 6. New pavement structure configuration incorporating anti-fatigue layer

manufacturing defects due to non-homogeneous compaction temperature and produces denser and more stable layers. Therefore, with excellent mechanical performance and waterproofing properties (air voids contents lower than 3%).

Compact asphalt technique can be used to lay surface layers or waterproofing layers with asphalt binder courses. It can also be used to produce two-layer asphalt base courses. These base courses work as one but each half of them can have a different and optimum composition for the exact position where they will be placed. For example, a good solution would be using a harder bitumen and higher RA contents in the upper part, while using softer and polymer modified bitumen for the bottom. With such configuration, the resulting compound base course would have high stiffness and bearing capacity near the top, while high elasticity and resistance to fatigue near the bottom.

The process requires simultaneous supply of both materials, usually form different asphalt plants. Once on-site, a material transfer vehicle feeds alternately separate hoppers with both materials. High compaction screeds are normally used, which produce a high level of pre-compaction in the bottom course. This makes possible to reach the final density requirements by simply using a medium weight tandem roller.

Compact asphalt technique is just an example of what a combination of advanced means and optimised logistics to coordinate the whole process can achieve. Both aspects are nowadays being boosted to a completely different level never seen in history, thanks to the digital revolution [18] that asphalt industry is living, hand in hand with the latest developments in robotics, machine-to-machine communication, sensors, big data, artificial intelligence and electrification, among others.

This includes, for example:

- Smart asphalt plants fully equipped with automatic production and control systems.
- Advanced transport vehicles, such as push-off trailers and advanced isolating materials, which help to deliver the mix with homogeneous temperature.
- Smart paving and compaction equipment with continuous and autonomous temperature and density monitoring.
- Job-site logistics tools to interconnect all previous stakeholders and optimise the

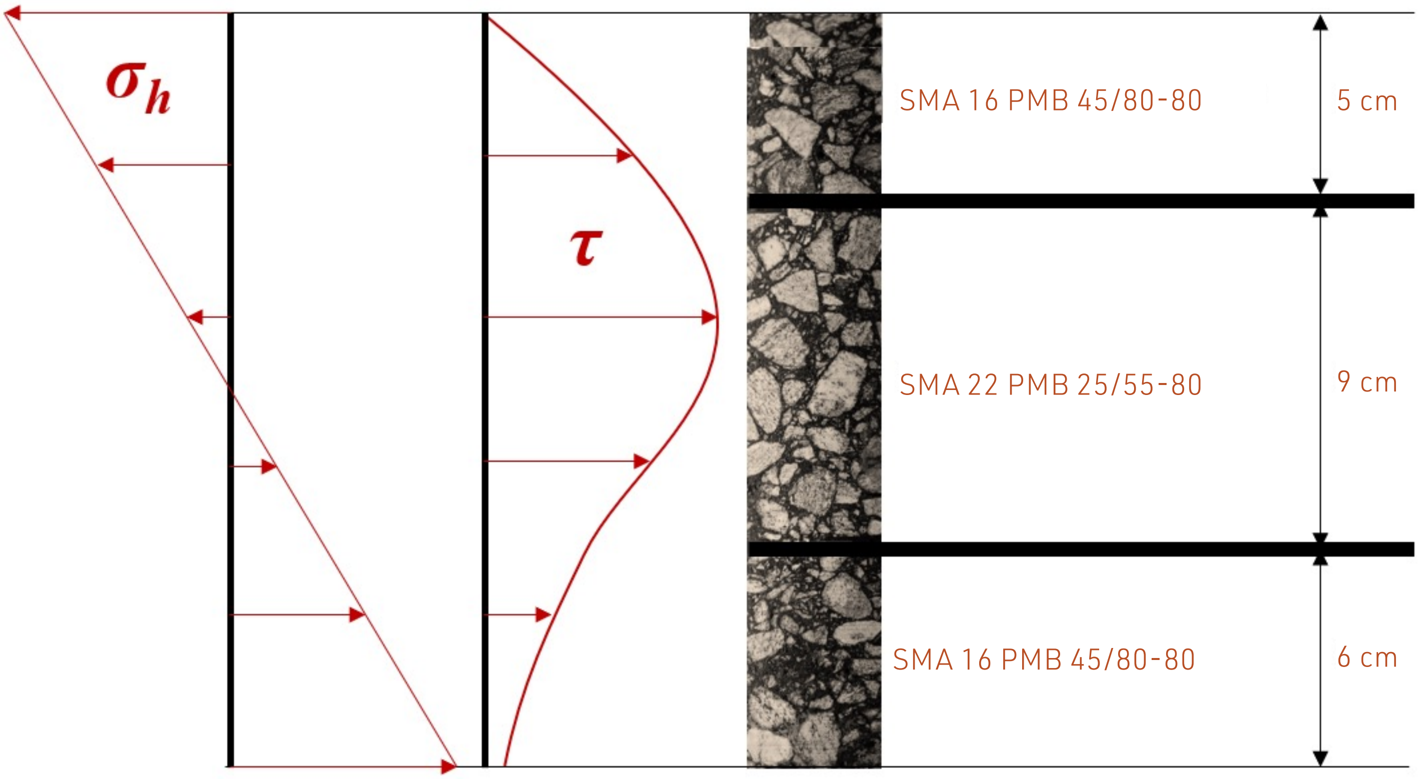


Figure 7. Triple-SMA pavement structure configuration

production, delivery and functioning pace at which each of them is working.
- Intelligent asphalt quality and roads inspection to detect at the earliest possible weak points in the pavement and repair them before they create bigger concerns.
- Smart asset management systems to optimise the performance of the road network during its service life.

By means of these disruptive technologies, the sector is taking a huge step forward to increase and multiply production efficiency, while maximising product quality.

4. New design methods

Due to the enhanced road requirements of VERRs, the design of pavements, where a large amount of such traffic is expected, must be optimised a-la-carte, through computational dimensioning. Nowadays, there are different tools, such as PaDesTo 2008-15 [19], which is conform to the German guidelines and calculates the pavement bearing capacity and deterioration, layer by layer, according to several damage criteria, such as bottom up fatigue cracking in asphalt base courses or plastic deformations in the upper bituminous asphalt layers and unbound sub-layers. Other models, such as the Layeps (Czech Republic [20]), Asdim (Austria [21]) or ALIZE-LCPC (France [22]) integrate the tools for structural design of heavy-duty pavement for ports and other industries. Users can define specific pavement loadings (geometry, intensity...) like reach stackers, straddle carriers and others like. Analysis is conducted so that all stresses and strains are calculated in the pavement structure subjected to this user-defined loading. Damage analysis is also possible for evaluation of the design thicknesses.

The main inputs for these models are:
- The relevant design traffic, in equivalent standard axle loads (ESAL). For this, it must be considered that not all the VERRs produce the same level of damage.
- Climatic conditions, such as the expected temperature in the bituminous layers or the needs of frost-resistant pavement.
- Material properties of every bituminous layer (e.g. rheological behaviour, fatigue and rutting performance) and granular sub-layers (e.g. bearing capacity, rutting performance, etc.).

Over the last years, a lot of new pavement design solutions were developed for airfields, where pavements must resist in good condition extremely high loads. The basis of such systems can have application in pavements subjected to high-stress conditions.

Examples of this, are the software applications of the Federal Aviation Administration [23-24] to support pavement design and pay reductions for airport pavement projects. These include [25] among other programs:
- FAARFIELD 1.42 [26]: standard thickness design software accompanying AC 150/5320-6F Airport Pavement Design and Evaluation.
- COMFAA 3.0 [27]: as introduced in version B of AC 150/5335-5, is the recommended method to determine airport runway, taxiway, and apron pavement strength with the Aircraft Classification Number - Pavement Classification Number (ACN-PCN) method. The software is capable of calculating Aircraft Classifications Numbers in accordance with the International Civil Aviation Organization (ICAO) procedure.

5. Upgrading of road network

Many existing pavements will need to be adapted over the coming years to accept increased traffic loads and the circulation of VERRs. Such adaptation will mainly consist of strengthening and/or widening of the existing pavement.

5.1 Strengthening of the existing pavement

When a pavement needs to meet higher traffic demands, strengthening can be achieved by either increasing the thickness or stiffness of the road base or improving the resistance to permanent deformation.

5.1.1 Increasing the thickness or stiffness of the road base

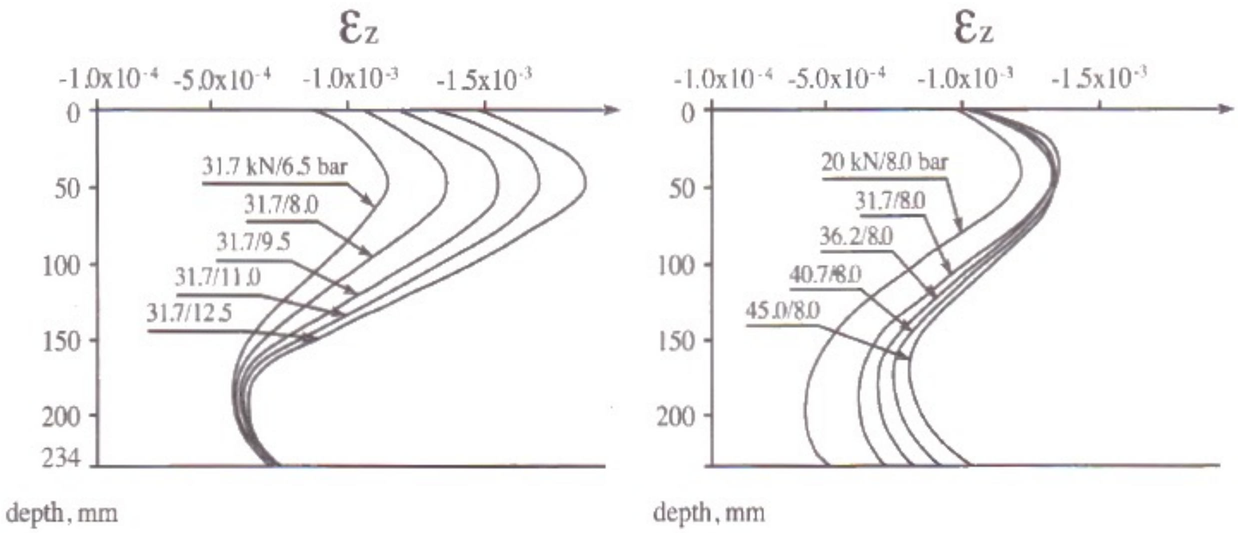
The required increase in structural strength can be calculated from the expected number of axle passages using available design methods. The overlay type and thickness depend on the amount of traffic and the strength of the existing pavement.

The latter can be estimated from the existing thickness and the equivalent number of standard axles passed or can be calculated e.g. by Falling Weight Deflectometer (FWD) measurement.
As shown in Figures 8 and 9 and as far as structural design is concerned, the effects of increasing axle loads (Figure 8-right) are relevant: the strain at the bottom of the pavement (which predominantly determines the resistance to fatigue cracking) increases as well.

As a rule of thumb, it can be stated that double the number of standard axles requires 20-25 mm extra thickness of asphalt courses.

By increasing the stiffness of the road base by a factor of 5, the predicted number of standard axles that the pavement will carry is increased by a factor of 5 to 10. It should be noted that this can be applied to all asphalt layers, but the most significant contribution will be made by the road base.

In general, both the measures to strengthen the structure and to increase resistance to permanent deformation are carried out together.



Course of vertical strain with constant single tyre load (31.7 kN) and variale inflation pressure.

Course of vertical strain with constant inflation pressure (800kPa / 8 bar and variable single tyre load.

Figure 8. Effects of tyre inflation pressure and wheel load on vertical pavement strain [28]

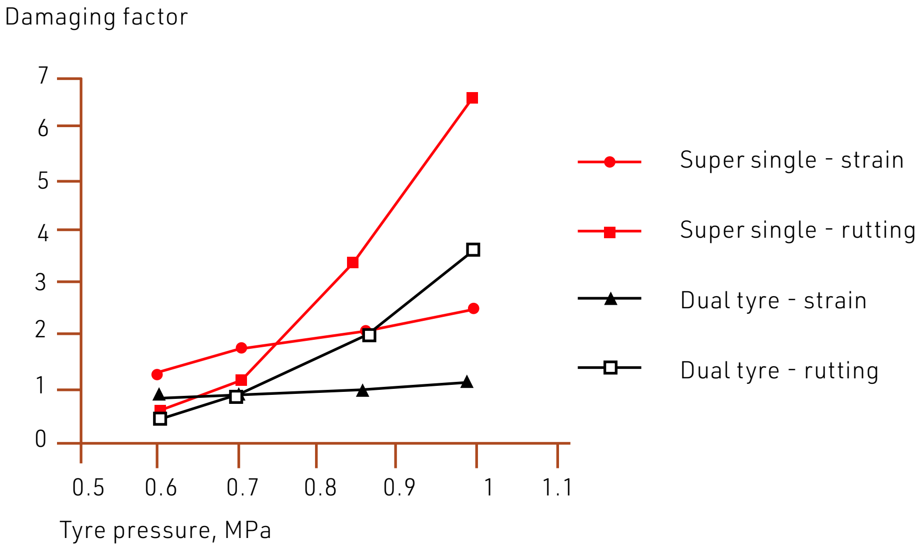


Figure 9. Damaging factor at increasing inflation pressure (axle load 100 kN) [29]

5.1.2 Increasing the resistance to permanent deformation

Where resistance to permanent deformation needs to be improved, layers, which do not fulfil the requirement are removed and replaced by new mixtures designed to bear the increased loads. In principle all deformable layers should be removed; in practice it is always a question of how deep to go.

In Figure 10 the theoretical development of the shear stresses (which are considered to be most relevant for permanent deformation) in a half-infinite space is illustrated. In a pavement maximum shear stresses occur at 50-80 mm below the surface in the case of moving traffic; in cases of accelerating/decelerating traffic (e.g. at intersections) these maxima will occur over the upper 60-100 mm. Where there is insufficient resistance to permanent deformation, the material should be renewed at least over this thickness; the resistance to permanent deformation of the remaining material should be considered carefully.

5.2 Road widening

Where there is a substantial increase in vehicle numbers, existing roads may have to be widened. This usually means that an additional lane will be built as the new inside lane, bearing the largest number of VERRs, and therefore the highest traffic load (unless the road alignment is also changed). In such cases the question arises as to how to design such a widening and how to carry out the construction with the least disruption to traffic - especially as road-widening projects are normally a response to heavy traffic congestion.

In countries, such as the Netherlands, a significant part of the highway system has been widened over the last years, always designing such actions with low maintenance requirements to reduce user delays.

In this sense:

- Road widening can be designed in the same way as new pavements for heavy duty traffic as the design models are sufficiently reliable.
- When constructing on subsoil with a low bearing capacity, the settlement of the embankment will cause most problems and not the pavement itself. Therefore, such embankments should be constructed to the highest quality level; no concessions in construction quality should be accepted simply to shorten lane closure periods.
- As settlement cannot be prevented on weak subsoil, asphalt pavements should always be used because of their flexible nature and ease of repair.

There are no situations where asphalt is unsuitable.

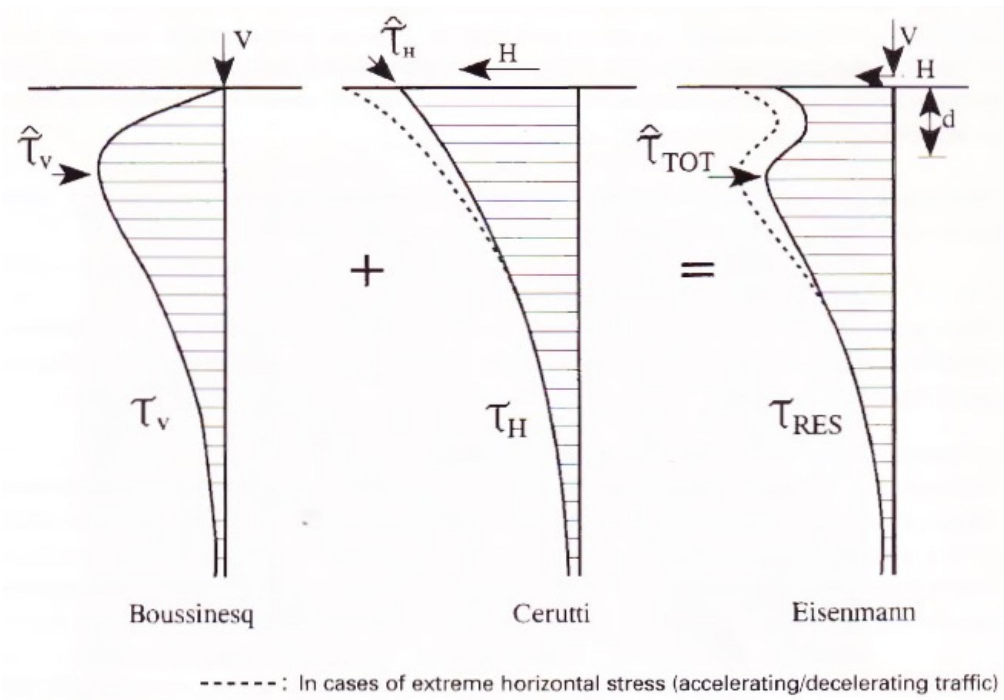


Figure 10. Development of shear stresses in a half-infinite space under vertical and horizontal loading [30]

6. Conclusions

In order to meet the current EU requirements, roads must be resilient, durable and require minimum maintenance operations and traffic disruptions. However, emerging factors are hindering these objectives, such as Climate Change, increasing road transport demand and axle loads, or the arrival of new types of vehicles with certain characteristics, which might produce the premature deterioration of the pavements.

To prevent this, high-performance pavement solutions can be adopted, progressively shifting our current pavement designs towards technologies conventionally used in highly stressed pavements. These solutions include the use of high-performance surface courses (e.g. SMA), high-modulus base courses and a series of advanced concepts, such as anti-fatigue bottom layers or triple SMA; all of this combined with the latest developments for optimum logistics and coordination among stakeholders.

Some of these solutions have been used for many years, while other have been developed over the last decade especially for this type of pavements. In all cases, the results were satisfactory.

For these reasons, the European Asphalt Sector is completely prepared and has capacity to give support to the traffic of new vehicles with enhanced road requirements, as well as to adapt the European road network wherever necessary.

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March 2022