



Project *Life*-NEEVE:

Innovate technologies to monitor and reduce Non-Exhaust Emission, particles and microplastics of Vehicles and pavements to improve air quality and human health

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Deliverable D2.4:

Properties and design of road pavements with focus on non-exhaust particle emissions

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**D2.4. Properties and design of road pavements with focus on non-exhaust particle emissions**

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SUMMARY

Deliverable D2.4 presents a comprehensive analysis of the influence of asphalt pavement design on the generation of Non-Exhaust Emissions, with particular focus on particulate matter produced through tyre–pavement interaction. The work includes a critical review of the state of the art, the selection and formulation of representative asphalt mixtures, and a structured laboratory testing campaign to evaluate mechanical and surface-related properties relevant to NEE.

The mixtures studied include both conventional configurations and innovative alternatives, with a focus on varying aggregate sizes and textures. Mechanical characterisation, friction tests, macrotexture measurements, drainage evaluation and particle loss analysis have been carried out using standardised protocols to assess each design’s suitability.

The results confirm the importance of aggregate selection, binder formulation and texture optimisation in limiting surface abrasion and wear-related emissions. Notably, the open-textured OSMA 11 mixture demonstrated an optimal balance between mechanical resistance, macrotexture development, and durability, making it a strong candidate for pilot-scale deployment in real-world conditions.

The outcomes of this deliverable contribute to the technical foundation of the LIFE NEEVE project, supporting the selection of low-emission asphalt surfaces for demonstration activities and informing future strategies for NEE mitigation through pavement engineering.



List of abbreviations and symbols

In this Deliverable abbreviations or symbols in the table below are often used.

Something like this may be included if it is useful. Otherwise, skip this page.

Abbreviation	Explanation	Comment
Partners, companies or institutions related to this project		
CTCON		Partner
CIEMAT		Partner
US		Partner
CHM		Partner
VTI		Partner
Technical terminology		
C1 (tyres)	Tyres intended for passenger cars	
C3 (tyres)	Tyres intended for trucks and busses	
EV	Electric vehicle	
Macrotexture	Road surface texture with spatial wavelengths between 0.5 and 50 mm	See definition in ISO 13473-1
Microtexture	Road surface texture with spatial wavelengths shorter than 0.5 mm	See definition in ISO 13473-1
Measures and units		
NMAS	Nominal maximum aggregate size	Unit: mm
MPD	Mean Profile Depth	Defined in ISO 13473-1, unit: mm
PSV	Polished Stone Value	Derived in meas. in a British method
NBM	Nordic Ball Mill (value)	Measure of wear of road aggregates



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1. Introduction

Air pollution remains one of the most serious environmental and public health issues in the European Union. According to the European Environment Agency, over 400,000 premature deaths annually in the EU are linked to poor air quality, with traffic-related particulate matter (PM) playing a significant role. Although emissions from vehicle exhausts have been progressively reduced thanks to increasingly stringent regulations, an emerging and largely unregulated source of pollution has gained prominence: non-exhaust emissions (NEE).

NEE are particulate emissions that originate not from the combustion engine but from mechanical processes such as tyre and brake wear, road surface abrasion, and the resuspension of deposited particles. These emissions are of particular concern due to their prevalence in urban environments and their direct impact on human health. Projections suggest that by 2030, NEE will account for up to 94 % of PM₁₀ and 90 % of PM_{2.5} traffic-related emissions across Europe. Moreover, NEE are not yet subject to binding regulations at the European level, despite their growing environmental relevance.

Among the sources of NEE, the interaction between tyres and pavement surfaces is especially critical. The mechanical friction during this interaction leads to abrasion of both the tyre rubber and the road material, releasing fine and ultrafine particles that are subsequently emitted into the atmosphere or transported through runoff into nearby ecosystems. These particles can contain a wide range of materials, including mineral aggregates, polymeric compounds, and potentially harmful substances such as heavy metals or microplastics. Therefore, asphalt pavement design has a direct influence on the amount and type of particles released.

In response to this environmental challenge, the LIFE NEEVE project, co-funded by the European Commission through the LIFE Programme, sets out to develop, validate, and disseminate innovative solutions aimed at measuring and reducing non-exhaust emissions from road traffic. The project, coordinated by the University of Seville and comprising a consortium of 10 partners from Spain, Sweden, and Germany, adopts a multidisciplinary and system-wide approach, integrating technological developments in pavements, tyres, and braking systems, as well as regulatory, awareness-raising, and policy-oriented actions.

This deliverable explores in detail the contribution of pavement design to NEE, presenting an integrated analysis of how material selection, structural configuration, and surface characteristics influence particulate emissions arising from tyre-pavement interaction. In this context, laboratory-based research activities have been conducted to assess the mechanical and environmental behaviour of a range of asphalt mixtures, with the goal of identifying those configurations that best contribute to the reduction of NEE without compromising durability, safety, or performance.

By establishing a comprehensive and standardised evaluation framework, Deliverable D2.4 lays the foundation for selecting and validating low-emission pavement solutions to be implemented in real-world pilot scenarios later in the project. In doing so, it supports the overarching ambition of LIFE NEEVE: to contribute to the transformation of urban mobility systems towards more sustainable, healthier, and cleaner transport infrastructure.



2. Purpose and objectives

The purpose of Deliverable D2.4 is to examine how the design, material composition, and construction characteristics of asphalt pavements can influence the generation and mitigation of non-exhaust emissions (NEE), with a specific focus on particle emissions caused by tyre–pavement interaction. This analysis forms a core component of the LIFE NEEVE project, which aims to develop integrated and scalable solutions to reduce particulate pollution from road traffic.

The deliverable responds to the need for a systematic and evidence-based evaluation of pavement types, considering the fact that NEE from road surface wear remains largely unregulated and poorly quantified. While existing knowledge recognises the role of pavement abrasion in contributing to PM10 and PM2.5 emissions, there is limited data on how different asphalt configurations, materials, and textures affect the formation, suspension, and potential retention of particles. Deliverable D2.4 contributes to closing this knowledge gap by integrating a comprehensive literature review with targeted laboratory experiments.

The specific objectives of this deliverable are as follows:

- To characterise the mechanisms by which pavement surface properties contribute to NEE, including both direct emissions (from pavement wear) and indirect emissions (from tyre rubber abrasion).
- To define and select a range of representative and alternative asphalt pavement types for evaluation, including conventional mixtures (SMA 11), porous configurations and innovative formulations for this particular aim.
- To design laboratory test protocols capable of determining the mechanical behaviour, friction characteristics, macrotexture, and drainage properties of each pavement type, using harmonised methods aligned with European standards.
- To analyse and compare the performance of selected pavement solutions in terms of their potential to reduce NEE, especially PM10 and PM2.5 emissions, while considering secondary factors such as durability, skid resistance, and expected service life.
- To provide a technical foundation for the selection of the most promising low-emission pavement designs to be used in LIFE NEEVE pilot demonstration sites, ensuring that these solutions are not only effective but also feasible for replication across different European contexts.

In summary, Deliverable D2.4 aims to bridge the gap between fundamental materials science and applied environmental performance, contributing robust evidence to support the project's overarching goals. It also creates a solid basis for further development, field validation, and policy dialogue concerning the role of pavement technologies in sustainable urban mobility.



3. State-of-the-art analysis

3.1. Background

While interacting with vehicle tyres, road surface pavements are abraded. The rate of abrasion depends on both paving and traffic properties. The abrasion products range from larger fragments to submicron particles and are mainly composed of ballast rock aggregate material, but the matrix will also contribute. Depending on size, particles are either deposited on or near the road or transported via runoff water to recipients downstream or suspended by traffic into the air and deposited further away from the road.

Although road surface abrasion is a universal phenomenon, it becomes significantly more pronounced in regions where studded tyres are commonly used during winter months. The widespread introduction of these tyres in the 1960s across Nordic countries, as well as in Germany, Japan, and parts of North America, quickly revealed their detrimental impact on pavement durability. Accelerated rutting and surface degradation led to substantial maintenance costs for road authorities. As a consequence, Germany prohibited the use of studded tyres as early as 1975. In Japan, urban bans followed in the 1990s, driven not only by infrastructural damage but also by the observation that studded tyres contributed to elevated concentrations of airborne particulate matter.

The adoption of the EU Air Quality Directive in 2010 further underscored the need to address this issue, particularly in Nordic countries, where road wear was recognised as a major contributor to PM10 emissions. This regulatory context has since prompted increased efforts to identify technological and material-based mitigation strategies aimed at reducing pavement-related non-exhaust emissions.

The original generation of studded tyres incorporated steel studs, which were subsequently refined to use lighter-weight alloys and smaller dimensions in order to reduce their destructive impact on pavement surfaces. In parallel, road engineering practices evolved to incorporate more abrasion-resistant pavement designs, where both the structural composition and the selection of materials played a decisive role in improving durability under aggressive wear conditions.

Mineral particles from road pavements have been shown to have adverse health effects and toxicological studies show differences in effects depending on aggregate materials. Some minerals, e.g. quartz and asbestos, are well known to cause airway diseases in working environments. To mitigate both emissions and toxic potential of NEE from road pavements is an important measure to reduce environmental and health effects of NEE from road traffic.

3.2. Method

In addition to consolidating the existing body of knowledge generated by VTI (Swedish National Road and Transport Research Institute), a comprehensive literature review was conducted. This review leveraged multiple scientific databases and tools, including Scopus, Web of Science, Google Scholar, Scopus AI, and the AI-assisted platform Elicit, to identify and analyse the most recent and relevant publications related to non-exhaust emissions from road pavements. The objective was to ensure that the state-of-the-art analysis reflected current scientific understanding and incorporated the latest research findings in the field.

3.3. Road surface properties influencing NEE

3.3.1. *Standard asphalt*

3.3.1.1. Construction

Standard asphalt mixtures, typically used in Europe (such as SMA or AC pavements) are composed of a blend of mineral aggregates of varying sizes, combined with a binder matrix (based on bitumen) and, where necessary, additives to enhance adhesion or the mechanical performance of the asphalt solution. In this context, it is worth mentioning that the aggregate skeleton provides the primary structural strength of the asphalt layer, while the binder fills the voids, ensuring cohesion and durability under traffic loads.

The gradation curve of the aggregate mix (distribution of particles size) is designed to meet specific performance criteria, including load-bearing capacity, surface texture, and resistance to deformation. In SMA mixtures, the structure is typically gap-graded to create a stone-on-stone contact network, offering high resistance to rutting. In contrast, AC mixtures tend to have a more continuous gradation, balancing flexibility and compactness.

The binder matrix must be formulated not only to ensure adequate workability during paving operations but also to withstand climatic stresses and repetitive loading from traffic. Modifiers additives, such as polymers, fibres or rubber may be added to improve pavement performance in particular demanding conditions. Additionally, filler materials are often included to improve bitumen mastic stability.

The final pavement performance strongly depends on how well the material design, layer thickness, and compaction are adapted to local environmental conditions and traffic categories. In the context of non-exhaust emissions, particular attention must be paid to aggregate selection and surface texture, as these parameters directly influence both abrasion resistance and particulate generation potential.

D2.4. Properties and design of road pavements with focus on non-exhaust particle emissions

3.3.1.2. Aggregate quality and characterisation methods

The rock aggregates mechanical properties play a major role in the abrasion resistance and overall durability of asphalt pavements, especially in environments subjected to intense traffic or aggressive wear conditions such as studded tyre use. The selection of aggregates with suitable mechanical performance is therefore essential in reducing both pavement degradation and non-exhaust particulate emissions.

Several standardised laboratory tests are commonly used to characterise the abrasion, fragmentation and polishing resistance of aggregates:

- Nordic Ball Mill (NBM) test, widely used in Nordic countries, evaluates abrasion resistance under simulated studded tyre conditions. According to Figure 1, lower NBM values (depending on the nature of the aggregates) indicate lower mass concentrations of PM10 particles in the total abraded material.
- Los Angeles (LA) abrasion test assesses the resistance to impact and grinding action, typically applied to those aggregates used in high-traffic intensity pavements. In this case, as shown in Figure 2, it is difficult to establish a strong relationship between Polished Stone Value (PSV) and the concentration of PM10 in total abraded material, but it can be observed that higher PSV values usually tend to have lower PM10 mass concentration.
- Micro-Deval test measures the resistance to wear under wet conditions and rotational movement, providing a good indicator of aggregate breakdown in the presence of water and mechanical stress.

These tests yield complementary data, and their results are often used in combination when specifying aggregates for high-performance asphalt mixtures. Studies have shown strong correlations between these test values and observed PM10 emissions in pavement wear simulations, confirming that aggregates with lower abrasion indices tend to produce fewer airborne particles.

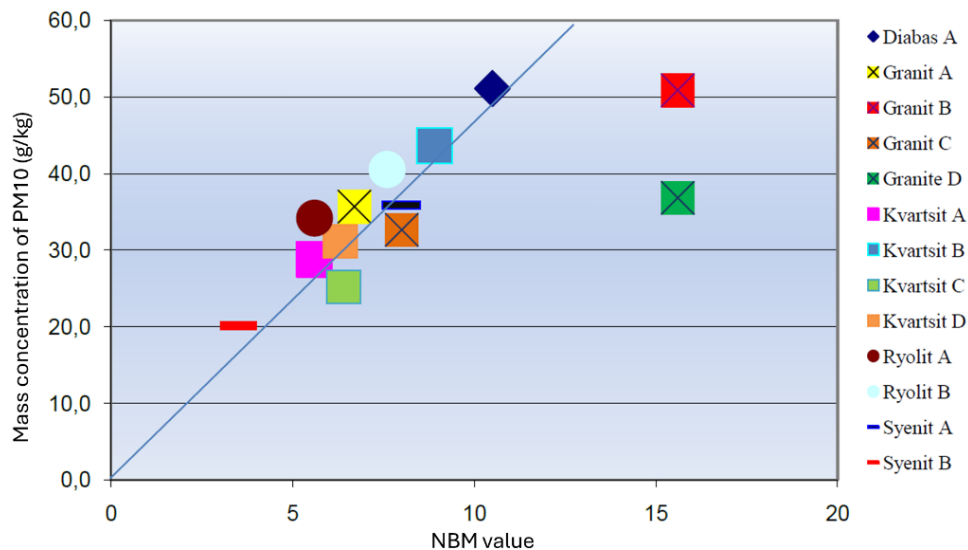


Figure 1. Relation between Nordic Ball Mill (NBM) value and concentration of PM10 in total abraded material for a number of different rocks [Döse & Åkesson, 2011]

D2.4. Properties and design of road pavements with focus on non-exhaust particle emissions

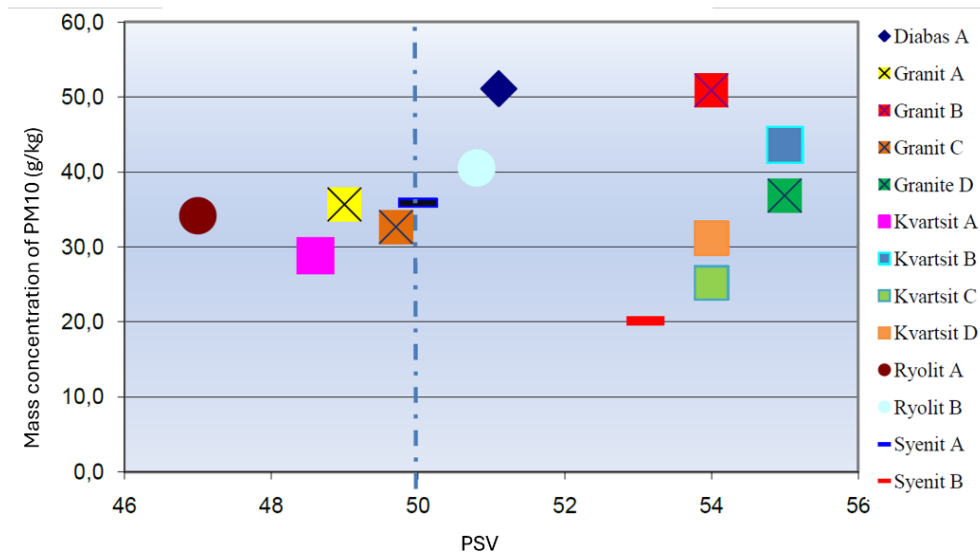


Figure 2. Relation between Polished Stone Value (PSV) and concentration of PM10 in total abraded material for a number of different rocks [Döse & Åkesson, 2011]

In line with these previous considerations, several studies have investigated how petrographic characteristics of aggregates influence their mechanical behaviour under stress. For example, Johansson et al. (2011) studied the influence of rock properties affecting the technical properties. Their findings revealed that for granitoids content of mica correlates to micro-deval and NBM values, grain size correlates to LA and NBM values and frequency of micro cracks correlates to micro-deval value for coarse aggregates (31.5/50 mm). For gabbroids, mica content correlates to LA, micro-deval and NBM values, and frequency of micro cracks correlates to LA, micro-deval and NBM values (see examples in Figure 3).

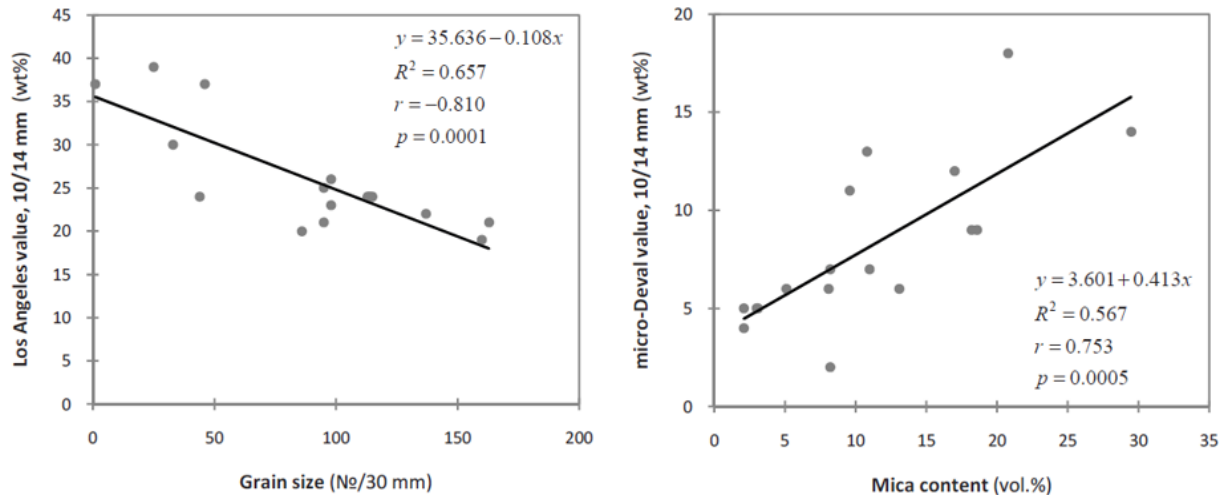


Figure 3. Effect of grain size on Los Angeles value (left) and of Mica content on micro-Deval value (right) for granitoid rocks. Examples from [Johansson et al. 2011].

D2.4. Properties and design of road pavements with focus on non-exhaust particle emissions

Wear resistance of the whole pavement can be studied both in field by following up on wear developments or in full-scale laboratory set-ups, like road simulators. For road construction purposes, the properties of the rock aggregates themselves are investigated for application in different road construction types suited for different traffic conditions and climates. Hardness, resistance to abrasion and resistance to fragmentation are examples of properties tested in different procedures and equipment. Resistance to abrasion is considered to best reflect pavement wear from studded tyres.

Using the road simulator at VTI, a large number of studies on abrasion resistance of different pavement constructions and aggregate materials have been made. Figure 4 shows both the influence of different rock types used as aggregates and the influence of using a more wear resistant construction, SMA (stone mastic asphalt) instead of DAC (dense asphalt concrete). Using diabase generates about double as high pavement abrasion compared to porphyry. Using SMA results in between 15 and 40 % lower abrasion compared to using DAC.

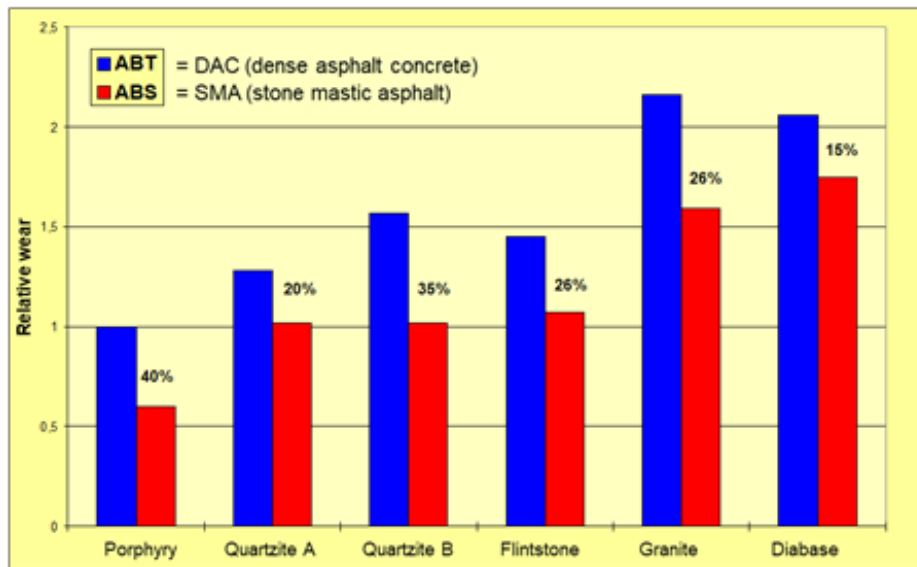


Figure 4. Influence of choice of rock aggregate and pavement construction on relative wear in road simulator tests

Further supporting these findings, PM10 emissions resulting from pavement wear caused by studded tyres have been studied using the VTI full-scale road simulator. The results demonstrate a clear correlation between aggregate abrasion indicators—specifically the NBM value and the Los Angeles LA value and the levels of PM10 generated. Among these two test procedures, according to Figure 5, the NBM value showed a slightly stronger correlation with PM10 emissions, indicating that aggregates with higher abrasion indices tend to release greater quantities of respirable particles when subjected to mechanical wear [Gustafsson & Johansson, 2012]. These observations underscore the relevance of aggregate selection not only for structural durability but also for minimising non-exhaust particulate emissions.

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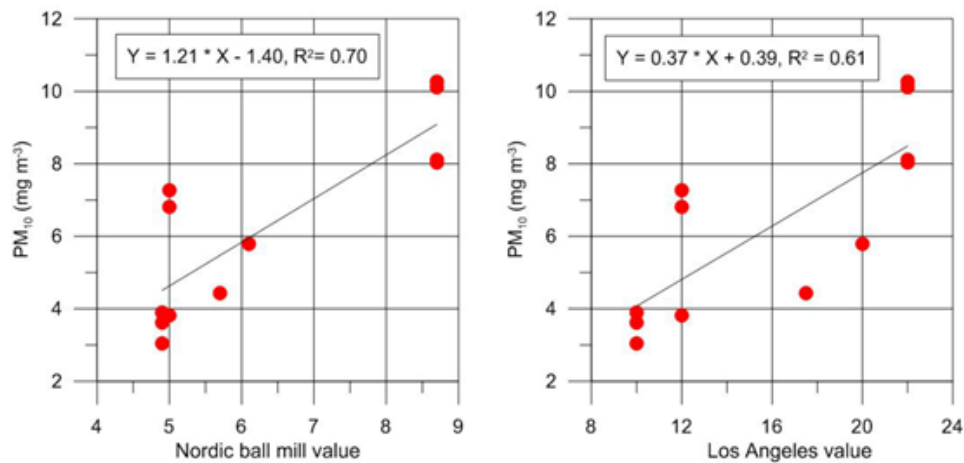


Figure 5. Relations between Nordic abrasion value (left) and Los Angeles value and PM₁₀ at 50 km/h, measured with TEOM for all SMA11 [Gustafsson & Johansson, 2012]

Building on this, [Gustafsson et al., 2011] demonstrated that, even when using the same rock aggregate type and identical SMA pavement construction, variations in the nominal maximum aggregate size (NMAS) significantly influenced particle emissions. Specifically, smaller aggregate sizes were associated with higher PM₁₀ concentrations, indicating an increase in surface abrasion under simulated wear conditions (see Figure 6). This suggests that reducing NMAS, while potentially beneficial for other pavement characteristics, may adversely affect the resistance to particulate generation, thus becoming a critical factor to consider in pavement designs aiming to reduce NEE.

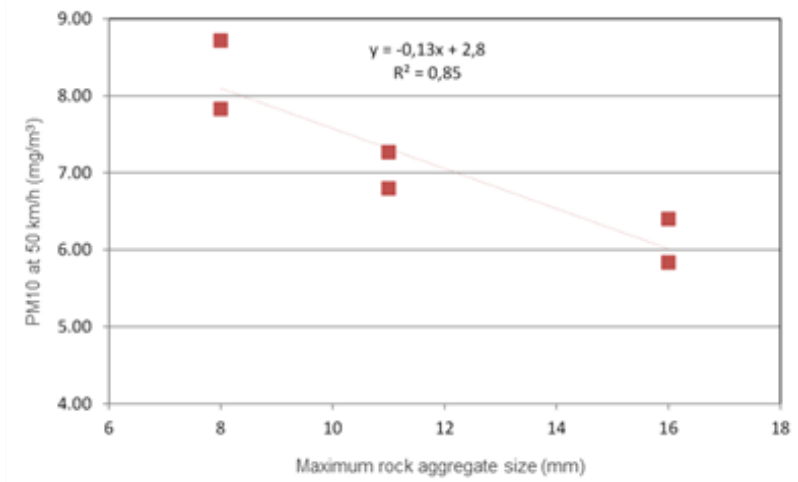


Figure 6. Influence of maximum rock aggregate size on PM₁₀ concentration in a road simulator set-up. [Gustafsson et al., 2011].

D2.4. Properties and design of road pavements with focus on non-exhaust particle emissions

While studded tyres are known to accelerate pavement wear significantly, it is important to note that studdles tyres (including both summer and winter variants) also contribute to surface abrasion and the associated emission of fine particles. For instance, [Gustafsson & Johansson, 2012] identified a notable contribution of calcium-rich particles to PM10 emissions in pavements constructed with limestone aggregates (see Figure 7).

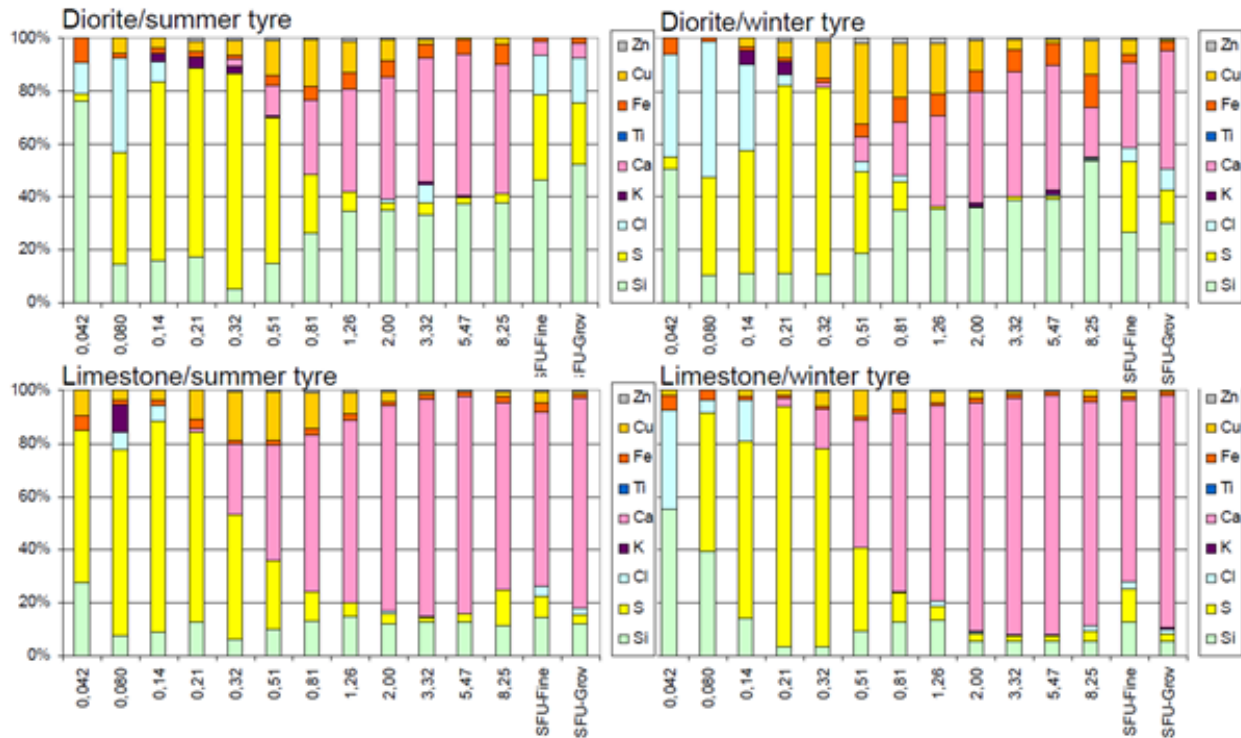


Figure 7. Elemental composition of particle size fractions within PM10 for diorite and limestone road pavements worn with summer tyres and studdles winter tyres, showing a dominant contribution of mineral elements, such as calcium and silica in the coarser fractions [Ravnikar Turk et al., 2009].

Further evidence of this effect was provided by studies using wheel-tracking devices and studless test tyres, which confirmed that pavements containing calcium-rich aggregates produced higher particle emissions compared to those dominated by silica-based materials. In particular, PM2.5 samples showed a strong correlation between elevated calcium content and increased particle concentration, as reported by [Fullova et al., 2017] and [Jandacka et al., 2021].

These findings reinforce the link between aggregate mineral composition, surface abrasion, and particulate matter emissions, and suggest that calcium-bearing rocks may present a greater environmental burden in terms of non-exhaust emissions compared to siliceous alternatives.

D2.4. Properties and design of road pavements with focus on non-exhaust particle emissions

3.3.1.3. Binder

The binder plays a critical role in the mechanical integrity and durability of asphalt mixtures, particularly with regard to their resistance to abrasion and surface degradation under traffic loading. Typically composed of bitumen, the binder forms the matrix that coats and binds the mineral aggregates, ensuring cohesion and distributing stresses throughout the pavement structure. Its viscoelastic properties significantly influence the performance of the mixture under varying temperature and loading conditions.

Among the different binder types, polymer-modified bitumen (PMB) has demonstrated superior performance in both laboratory and field applications. These binders exhibit enhanced stiffness, elasticity, and adhesion, contributing to increased resistance to abrasion, rutting, and ravelling, especially in porous asphalt mixtures where the matrix is more exposed to environmental and mechanical stresses [Chen et al., 2012; Gayfutdinov et al., 2021]. High-viscosity binders also perform well in resisting surface wear, particularly under heavy traffic and in extreme climates.

Key rheological properties used to characterise binder performance include the complex shear modulus (G^*), viscosity, and penetration index, all of which are critical parameters when selecting binders for specific applications [Molenaar & Molenaar, 2000]. Polymer-modified binders have been shown to offer additional resistance against chemical degradation, such as from hydrocarbon contamination, thereby enhancing the functional lifespan and ravelling resistance of permeable pavements [Rodríguez-Hernández et al., 2015].

From the perspective of non-exhaust emissions, the binder influences both the cohesion of fine particles and the stability of the mastic, affecting how readily particles are detached during tyre–pavement interaction. Therefore, the selection and formulation of the binder should consider not only traditional performance metrics but also its potential contribution to particulate emissions, particularly in highly trafficked or climatically demanding environments.

3.3.2. *Alternative road paving*

3.3.2.1. Porous asphalt

Porous asphalt (PA) is used to drain water from the road surface but also reduces noise from tyre and pavement interaction. This is due to the open construction where sound is absorbed in the void system. The pavement type is commonly used in parts of Europe, with The Netherlands has the highest percentage of roads where PA is used.

PA is less used in the Nordic countries, mainly due to harsher winter conditions and use of studded tyres which make the pavements prone to ravelling and the pavement wear dust from studded tyre use clogs the voids. Clogging destroys the draining and noise reducing functions. To maintain the functions, the pavements need to be cleaned and with a high dust production and fast clogging, this makes maintenance expensive.

D2.4. Properties and design of road pavements with focus on non-exhaust particle emissions

The process causing clogging also has a positive aspect. The road dust accumulating in the voids of the PA is removed from the suspension forces of the traffic and will not contribute to airborne particle emissions. This effect has been shown in e.g. [Norman & Johansson, 2017]. The initial obvious effect on PM₁₀ concentrations the first season after application of a PA, diminished during the following seasons, due to clogging. [Svensson et al., 2024] only evaluated the effect during the first season but could also show that the PA remained moist for longer in the morning during the dusty early spring, which contributed to reduced resuspension of PM₁₀ and lower PM₁₀ concentrations along the PA road (Figure 8).

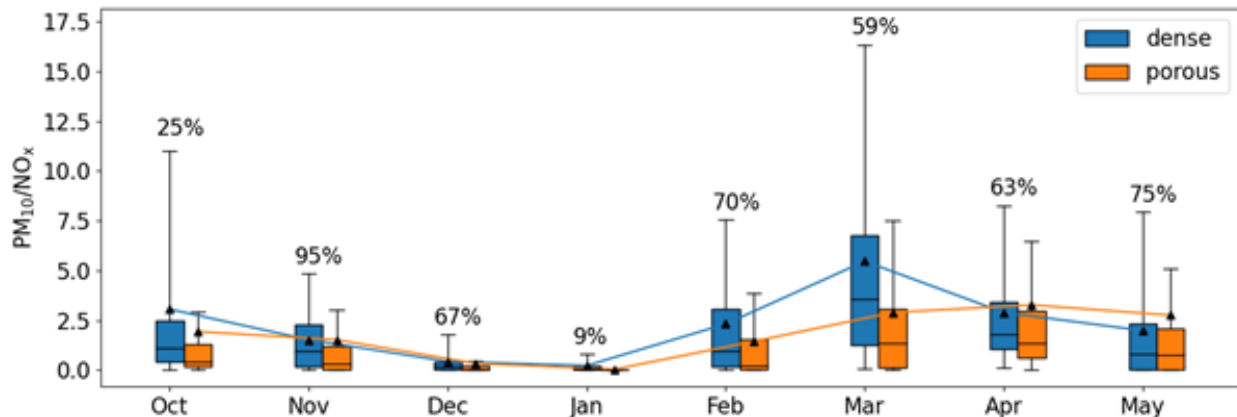


Figure 8. Ratio of PM₁₀/NO_x at a dense and a porous asphalt along the same road with the same traffic, [Svensson et al, 2024]

3.3.2.2. Cement concrete

Concrete pavements can offer superior abrasion resistance compared to asphalt, particularly when using high-strength mixes. Increasing concrete strength from 50 to 100 MPa can reduce abrasion by approximately 50%, with 150 MPa concrete showing comparable abrasion resistance to high-quality granite and potentially lasting ten times longer than asphalt pavements [Gjørsv et al., 1990]. Abrasion resistance is directly related to matrix proportions and bulk properties, with wet conditions generally resulting in worse performance [Ghafoori & Sukandar, 1995]. Early-opening-to-traffic concrete pavements can be designed with varying cement factors and admixtures to achieve desired abrasion resistance [Ghafoori & Tays, 2007]. Polymer modification of cement mortar, such as using carboxyl styrene butadiene rubber latex, can significantly improve abrasion resistance and flexural strength, although it may reduce compressive strength [Zhou et al., 2020]. Flexural strength shows a stronger correlation with abrasion resistance than compressive strength in cement mortars.

In a recent review, Subedi et al. [2025] concluded that abrasive resistance in concrete pavements relate to how well the surface hardness of the coarse aggregates used, how well they adhere to the paste and their wear resistance. As with asphalt, the rock aggregates used are central to abrasion resistance.

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The particle emissions from cement concrete pavements have been compared in road simulator tests [Gustafsson et al., 2019]. The two concrete pavements tested had lower total abrasion than the reference asphalt but emitted higher amounts of PM₁₀. A markedly higher contribution of calcium in PM₁₀ from the cement concrete pavements indicated a higher contribution to PM₁₀ from the cement binder compared to from the bitumen of the asphalt. A study where TiO₂ were mixed into the cement binder in a cement concrete pavement confirmed that the cement binder is a relatively important PM₁₀ source from studded tyre wear of cement concrete pavements [Gustafsson et al., 2013].

3.3.3. Alternative materials in asphalt

3.3.3.1. Steel slag

Steel slag aggregates have shown higher abrasion and skid resistance compared to conventional rock aggregates in pavements. Studies have demonstrated that steel slag exhibits lower abrasion rates, higher initial angularity, and more durable wear resistance than natural stones like granite and limestone [Wang et al., 2023, Wang et al., 2024]. The microtexture of steel slag aggregates features a rougher surface with more contact points, contributing to better skid resistance [Wang et al., 2023]. When incorporated into concrete paver blocks, steel slag aggregates improved mechanical properties and abrasion resistance [Abdelbary & Mohamed, 2016].

Long-term studies have also indicated that steel slag maintains superior initial and sustained skid resistance over time [Wang et al., 2024]. Predictive models based on friction indicators and polished stone value (PSV) tests have been developed to assess the degradation of skid resistance for various aggregates, including steel slag, in road pavements [Crisman et al., 2019]. In tests of nine different slags for use in pavement constructions for Nordic conditions, Viman [2015] found that many of the tested slags had aggregate characteristics similar to very good rock (see Figure 9). Nevertheless, note that the NBV range is very large, so it is important to select the “right” steel slag material.

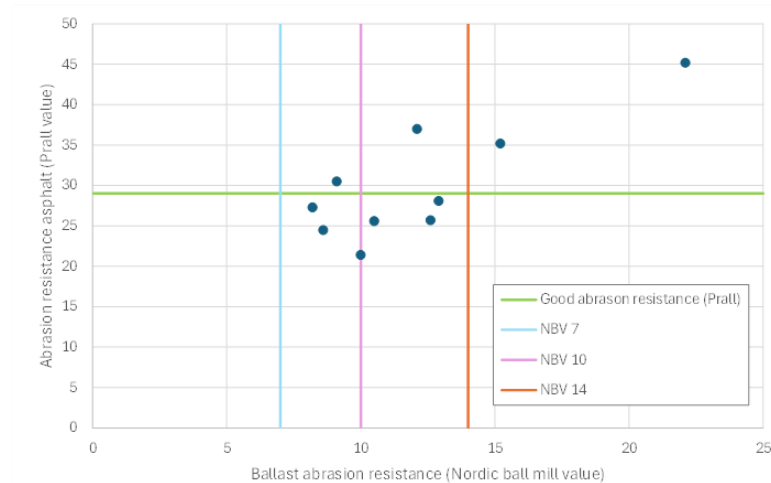


Figure 9. Slag asphalt sample abrasion resistance according to Prall method as function of ballast abrasion resistance according to Nordic ball mill method. Data below the green line have good abrasion resistance. The NBV 7, 10 and 14 lines are requirements for roads with different AADT in Sweden. Lower NBV is more abrasion resistant (after [Viman, 2015])

D2.4. Properties and design of road pavements with focus on non-exhaust particle emissions

Particle emissions from steel slag pavements specifically are rarely reported in literature. In Viman & Gustafsson, [2015] comparison of PM10 emission between two constructions with slag (SMA11 and SMA16) was made. The results showed that emissions were comparable to an SMA with the most wear resistant rock in the study (granite with a Nordic ball mill value of 6). The PM10 composition differed markedly from the rock-based pavements, with a higher content of Fe, Ca, Mn and Cr and lower content of Si and K. It was also noted that, after a long time of studded tyre wear, the remaining metal-containing slag aggregates protruded markedly from the surface of the pavement, posing a risk for damaging tyres and studs (Figure 10). However, this effect has not been observed in Swedish field tests of steel slag [Sandberg, 2023].



Figure 10. Steel slag aggregates protrusion after long pavement wear by studded tyres (Viman & Gustafsson, 2015)

It should be noted that the research about steel slag currently is intensive and absolutely one of the most popular subjects for PhD studies within pavement engineering. In only the last two years, one of the authors (Sandberg) has collected more than 50 new articles about the use of steel slag as road pavement aggregate, the vast majority of them from China.

3.3.3.2. Rubber

Tyre crumb rubber is used in road pavement construction in different ways. Full rubber pavements are rare but have been used experimentally for noise reduction in e.g. Sweden and Japan [Sandberg & Goubert, 2011]. Also pavements mixing some hard and sharp aggregate with rubber, with rubber content above 50 % by weight, have been tried [Sandberg & Kalman, 2005]. Common to all have been high noise reduction (8-12 dB) but unacceptably poor durability. A more common use is mixing rubber into the binder matrix, the so-called wet process. This may reduce noise emissions, but only marginally [Sandberg, 2010].



D2.4. Properties and design of road pavements with focus on non-exhaust particle emissions

Picado-Santos et al [2020] concluded in their review that crumb rubber asphalt (CRA) offers better durability and resistance to cracking and deformation compared to conventional asphalt, but there is no information about influence of abrasion or particle emission. Environmental benefits are the recycling of tyre material and the increased durability resulting in lower maintenance costs. Crumb rubber can also be used in cement concrete pavements and seem to increase abrasion resistance [Li et al., 2014, Noor et al., 2016].

Another way to produce rubber asphalt is to mix rubber particles as aggregate into the mix. This is known as the dry process. The expected advantages were somewhat lower noise emission and much better resistance against skid resistance on icy surfaces. The latter was found to be true. But wear or particle emissions were not explored. Some early experiments on this are described in [Sandberg & Ejsmont, 2002]. Very recently, a new project using the dry process and rubber particles up to 12 mm have been presented in Japan, with good results so far [Sahdeo, 2025].

As with many alternative materials, particle emission studies are rare also regarding rubber mixed pavements. Most publications focus on gaseous emissions in the production process and conclude that crumb rubber modified asphalt (CRMA) emits higher levels of both VOC and PAH [e.g. Tang et al., 2022, Zhu et al., 2024]. Also, TSP (total suspended particulates) emissions during the pave are high from CRMA and higher during from a warm mix than from a hot [Xiu et al., 2020]. Particle emissions from studded tyre wear of CRA were studied by Gustafsson et al. [2011] and showed that a gap-graded pavement with rubber mixed bitumen emitted less PM10 than an equivalent SMA construction in road simulator tests.

Pavements with substantial rubber contents have a certain potential of providing lower particle emissions. The reason is that rubber aggregate is elastic and may thus be resilient and “give way” to some of the stick-slip motions in the tyre/road contact patch. This would provide a “softer” way of transferring the tangential forces in the contact patch. A sign of this was obtained in the PERSUADE project when the rubber surface performed better than the reference asphalt in exposure to studded tyre wear [PERSUADE, 2015].

4. Pavements worth considering for tests in NEEVE

4.1. Introduction

Pavement surfaces (wearing courses) have different materials and different textures which more or less influence how much particles from the pavement surface that can be directly emitted when subject to rolling tyres. They will also have an indirect influence when tyres are affected by the pavement surface, as tyre rubber particle emissions and, therefore, the notion of **direct and indirect effect of pavement surfaces** on abrasion and on particle emissions is introduced.

- Direct influence refers to the influence of the construction, material and pavement properties on the abrasion and particle emissions of pavements.
- Indirect influence refers to the influence of the construction, material and pavement properties on the abrasion and particle emissions of tyres (i.e. tyre rubber). Both are important in the sense of NEE.

Although rubber abrasion is treated in another deliverable (D2.6) it cannot be neglected in D2.4 as the pavement has an influence on it, which must be considered when attempting to identify pavements with low NEE. The issue is very complicated since there is always an interaction between the pavement surface and the tyre. The question is somewhat related to the classic question: who came first, the hen or the chicken.

The matter becomes even more complicated since the pavements create emissions into the air but may also store some of the particles permanently or temporarily on or in their structure, for possible mix with water and drain off to the roadside. The latter may occur either on the pavement surface or inside the pavement, in the latter case if the pavement has interconnected voids (“porosity”).

4.2. Mechanisms of interest in the generation of particle emissions

This is a supplement to the State-of-the-Art chapter above, intended to provide a background for the selection of test pavements.

Pavement surface particles may be loosened by essentially two mechanisms: by stick-slip movements and by tyre tread impact on the pavement surface. None is unique in the NEE subject; instead both are active in most other effects in the tyre/road interaction, such as friction, noise and rolling resistance. The stick-slip mechanisms cause relative movements between tyre tread rubber and the pavement surface, which occur in the contact patch and at the trailing edge of the contact patch. This mechanism is necessary to transfer longitudinal and lateral forces between the rolling tyre and pavement, more at braking and acceleration or at driving in curves, than at constant speed on a straight road. But particles can also be loosened by “knocking”, i.e. tyre radial stresses when the rubber tread elements impact the road surface in the leading edge of the contact patch.

D2.4. Properties and design of road pavements with focus on non-exhaust particle emissions

A special mechanism both as stick-slip and as impact is when tyres are equipped with metal studs to provide improved friction on snowy or icy roads. In the north European countries and in local mountain communities where studded tyres are used, this is the most important cause of particle emission, and also pavement surface wear. As an annual average NEE, it of course depends on the duration of the winter season. In Sweden, Norway, Finland and Iceland studded tyres are largely used during up to half the year.

The energy in these mechanisms is consumed as friction and/or deflection and finally as heat (and sound). However, there is also energy required to separate particles from the body they are part of, i.e. the aggregate, mortar or binder of the pavement surface.

Also, the spreading of particles from the pavement and/or the tyre surfaces when emitted to the tyre surroundings require some energy, in this case coming from the wind turbulence surrounding the tyre when it moves along the road and displaces the ambient air. Also, the rotation of the tyre contributes energy to the throwing of particles away from the tyre tread and the trailing contact edge.

4.3. Pavement properties and construction which may give less direct NEE

The stick-slip movements will first (for a new pavement) slip-off the bitumen on top of the pavement surface, which in many European countries often is polymer-modified and also often mixed with rubber particles (known as asphalt rubber or rubber asphalt). This will substantially improve the friction properties of the surface, since tyre rubber on bitumen with possible water in-between is very dangerous. This polishing exposes the aggregate and the mortar to further polishing where the mortar (mix of sand particles and binder) which is in the top of the surface (and the part which is in touch with the tyre) more easily loosens from the pavement. Simultaneously, the aggregate is polished, and the smaller gradings are worn off quicker than the largest ones as they do not sit equally firm in the mix. The largest ones will stand the longest but will also get polished.

The polishing of the pavement surface by tyres can occur in five ways, depending on the aggregate material:

1. The stones are very resistant against polishing. Microtexture will remain as original a long time. This will create minor particle emission from the stones, but depending on the microtexture and macrotexture it can create significant rubber abrasion.
2. The original microtexture is polished away by the tyres stick-slip action, to leave "bald" but hard stones with low microtexture. This will create minor particle emission from the stones, but depending on macrotexture, rubber abrasion may be low.
3. Not only the microtexture but also the surface macrotexture is worn away, to leave bald stones which have lost more of the top layer. Here we will get high levels of particle emissions from the surface and also low rubber abrasion.
4. The next option is like the previous one, but when material is worn off the stones new microtexture on the stones will be exposed so the stones will still have significant microtexture. This will create high levels of particle emissions and also of rubber abrasion.



D2.4. Properties and design of road pavements with focus on non-exhaust particle emissions

5. When studded tyres are used, the studs will scratch the stones by also impact them, which may crack away parts of the stones. Usually this creates a lot of wear (loss of mass, both large and small particles) but simultaneously it may create or restore microtexture. This will also result in rubber abrasion. In countries which allow studded tyres, the action of the studs in the cold season will give good friction in the warm season, until the tyres have polished away the microtexture in the late autumn.

The resistance to polishing of the aggregate (normally the stones) is commonly tested by a British method called the Polished Stone Value test, with a resulting Polished Stone Value (PSV) characterising the aggregate. This is an important evaluation method for the skid resistance of road surfaces but also useful for testing how quickly a sample of aggregate becomes polished and smoother after repeated passes of tyres. There will be stones that have high PSV and high wear, as well as the opposite. The PSV will be interesting as a proxy value for microtexture and thus for friction and rubber abrasion.

To estimate the overall wear of the pavement aggregates, there are other methods that are more suitable, and which are mentioned in Section 5 (e.g. Cantabro test or Prall).

Consequently, it is favourable to select durable wear-resistant aggregates. High PSV is desirable for friction but not for particle emissions from the road or from rubber abrasion. It is also preferable to have a large aggregate that will protect the smaller aggregate and the mortar from the stick-slip actions. But the largest aggregates cannot be too large as there will be unwanted effects the larger they are, such as greater noise emission and rolling resistance. An optimum preferred by many road administrations worldwide is 11 or 13 mm (nominal maximum aggregate size, NMAS). In the Nordic countries (Sweden, Finland, Norway and Iceland) NMAS of 14 or 16 mm are preferred as they are not knocked-apart by impact and slip by studs so easily as the smaller sizes are. Usually, 11 or 13 mm are preferred also to reduce the risk of wet skidding or even hydroplaning. For noise and rolling resistance, however, one would prefer smaller NMAS, such as 4, 6 or 8 mm.

Also, the shape of the aggregate is important. Sharp edges are preferred for high skid resistance but not for low abrasion (especially abrasion of tyre rubber, see below).

Another crucial thing is how well the tyre tread can “envelope” the texture; i.e. how well the tyre tread can remain in contact with the pavement surface. The rubber will be in contact with the peaks (the larger aggregates) but will not be in contact with deep valleys between the largest aggregates. If the larger aggregates can be in close proximity to each other with only narrow valleys between them, the tyre tread will envelope just part of the larger aggregates, which should be and often are the most abrasion-resistance part of the pavement. The trick is to have the largest aggregates close to each other but still tightly held below the surface by binder and mortar. This “trick” is managed by porous asphalt pavements. Stone Mastic Asphalt (SMA) is a popular pavement type which has a reduced amount of small aggregates and larger amount of the maximum size, which creates a higher macrotexture but not necessarily higher texture impact on the tyre since the larger aggregates will be somewhat closer to each other than in a dense asphalt concrete (DAC or AC) pavement. The SMA pavements with high quality aggregates and properly paved are generally considered as the most long-lasting pavements.

D2.4. Properties and design of road pavements with focus on non-exhaust particle emissions

Surface dressings but with small, sharp and very durable aggregate (often dominated by the grading 2-4 mm) are commonly used to increase safety at road or street crossings where braking frequently occurs. They may cause severe abrasion of tyre tread rubber, but they also wear down more rapidly due to the small aggregate the stop-and-go traffic, which creates particles from the aggregate. See also the next sub-chapter.

NEE studies have focused mainly on the situation in dry weather. But in many countries rainy weather or wet road surfaces for other reasons, exist for a large time of the year. In rainy weather, or else when the pavement surface is wet, the water mixed with road particles will be splashed and sprayed off the pavement surface by the action of the vehicle tyres and the air turbulence around the vehicles. The heavily loaded truck tyres will suck up water mixed with dirt from the valleys in the surface and even from the voids in it in case of porous asphalt. This makes some of the NEE be moved to the road surroundings mixed with water to a smaller roadside area than when the weather is dry. A disadvantage is of course that the road dirt will be accumulated on roadside objects like road signs, private gardens, vegetation, roadside buildings, etc, apart from finishing-up in the soil or maybe drained away in ditches or waterways. But from the NEE and health point of view, this is better than particles spreading widely in the air.

As already is reported in 3.3.2.1, porous asphalt has a substantial potential to reduce particle emissions, at least when it is new and not clogged. But not only the porosity of PA may be a favourable factor but also that PA is usually constructed with among the best available stone aggregate in the top layer since a less durable material may lead to faster clogging. Furthermore, in PA compared to for example SMA there is less small aggregates and sand that can easier be worn off by the actions of traffic. Therefore, PA will no doubt lose some of its advantage in wear due to clogging but it has a potential to keep some of its minor advantages throughout the lifetime.

Another feature which is advantageous is to have a surface which is fairly smooth, which gives many contact points between rubber and texture. In this way the contact forces and stresses are shared among many contact points. This feature is enhanced if the maximum aggregate size is small and if the asphalt surface is well rolled after paving. It will also be enhanced by grinding as reported in [Vieira et al, 2018].

4.4. Pavement properties and construction which may give less indirect NEE from tyres

Pavement design and construction characteristics significantly affect the generation of indirect (NEE) via tyre-road interaction. Although a detailed exploration of these mechanisms is reserved for Deliverable D2.6, their relevance to the experimental configuration of the LIFE NEEVE project necessitates their early consideration within the present Deliverable (D2.4).

Sharp aggregates, such as when coming from crushed rock, will cut and brake loose rubber particles. This may be both from the impact mechanism and the stick-slip mechanism. The worst pavement type in this respect is surface dressing made of crushed stone. It is also known as “chip seals”. Such pavements are used primarily on country roads with low traffic. Therefore, on a global level this pavement type is not a serious cause of NEE.



D2.4. Properties and design of road pavements with focus on non-exhaust particle emissions

However, surface dressings but with small, sharp and very durable aggregate (often dominated by the grading 2-4 mm) are commonly used to increase safety at road or street crossings where braking frequently occurs. It is common to use as the aggregate a stone (Calcined Bauxite) which is mostly mined in China. This will probably be a serious source of NEE (mostly from tyre rubber but to a lesser extent from the aggregate) which occurs in busy areas where NEE may do a lot of harm to humans. These pavements are usually proprietary, i.e. commercial products. They may be especially preferred in countries or regions where aggregates with high friction are rare and insufficient at crossings.

Rolled mixes such as DAC, SMA and PA may also have crushed stones, but the rolling process will align the stones, so they do not penetrate into the rubber. Nevertheless, the tyre tread will envelope the macrotexture, so it is impossible to avoid some contact with sharp edges. Due to the wear-down of particularly sharp edges the particle emissions will be worst before this has happened but with time and wear, the sharp edges will disappear.

High microtexture of the pavement surface is needed to give the pavement high skid resistance. Therefore, when available, aggregates with high initial microtexture and high PSV are generally desired on our pavements. This has the compromise that it creates increased rubber abrasion through the stick-slip process. Also, high macrotexture is needed for traffic safety reasons; mainly at high speeds on wet roads and to avoid hydroplaning. There are indications that also this compromise rubber abrasion.

4.5. Pavements considered for NEEVE testing and their justifications

4.5.1. Introduction

In another part of this deliverable, the pavements selected for testing in laboratory environment are presented. This sub-chapter is a discussion about these pavements and why they were selected.

4.5.2. Reference pavement

Each study comparing pavement performance should have a reference pavement. In this case it will be SMA 11. One reason is that it is one of the most popular pavements in Europe and also used almost worldwide. DAC 11 or AC 11 would also be a very popular pavement although in many parts of Asia, the NMAS of 13 mm is preferred. But SMA 11 and DAC 11 have both been selected as reference pavements in noise calculations (as an average), as in the common European CNOSSOS model. This is a strong case for SMA 11 as our reference here. However, if possible, it would be desirable also to include a DAC 11.

D2.4. Properties and design of road pavements with focus on non-exhaust particle emissions

In Sweden, SMA 16 is the reference pavement in cases where one is desired. It is also mostly preferred in Norway and Finland. The reason is that it is the most dominating pavement on the national road network and also is very common in urban networks. It is so popular because it is the most durable pavement in the nation due to the wear by studded tyres in wintertime. SMA 11 has a significantly shorter lifetime than the SMA 16 where studded tyres are frequently used in wintertime. But for Europe overall and also globally, the SMA 11 is a better choice for reference.

4.5.3. SMA 11

Stone Mastic Asphalt (SMA) is gap-graded asphalt mixture with bitumen as a binder, composed of a coarse crushed aggregate skeleton bound with a mastic mortar. In general, SMAs are considered as one of the most durable and abrasion-resistant pavement types. This is because it is “rich of stones”, i.e. its grading has a high content of the NMAS and less of the medium sizes, which means that the tyres are mainly in contact with the largest stones. Consequently, these will take much of the loads and stresses from the tyres and if they are of high quality the pavement will wear less. The pavement type became popular in Sweden about 40 years ago, but in some other countries its introduction came later. A major reason is that the SMAs are more critical to pave in a homogeneous way, and often the first attempts may go wrong, but in the long run SMAs are winning.

SMAs get a rougher macrotexture than DACs due to the medium aggregate sizes are less than in a DAC, which means that the valleys between the largest stones will be deeper. An SMA 11 will typically have an MPD (Mean Profile Depth) of 0.9 to 1.2 mm and an SMA 16 will have MPD in the range 1.0-1.5. This gives high skid resistance but also high noise emission and high rolling resistance, so compromises are needed. Therefore, SMA 16 is used only when it is necessary because of studded tyres use. SMA 11 is often considered as a fairly good compromise.

It will be a challenge to nominate pavements with less abrasion and particle emissions.

4.5.4. SMA 8

SMA 8 is not likely to reduce road abrasion and resulting particle emissions. SMA 8 is significantly better for reducing noise emission and rolling resistance, without sacrificing skid resistance, since its MPD values will typically be from 0.6 to 1.0 mm. It is not known how much SMA 8 wears the tread rubber of tyres, but it is speculated that the lower macrotexture and the more contact points in the tyre/road contact patch may create somewhat less rubber particles. The hope is that SMA 8 will wear and give road particle emissions only marginally more than SMA 11 and perhaps that less rubber abrasion might balance out the possibly increased road abrasion. If so, when crucial compromises are needed with the mentioned parameters, SMA 8 could become a preferred choice in countries where studded tyres are not used.

D2.4. Properties and design of road pavements with focus on non-exhaust particle emissions

4.5.5. PA 11

Normally, a pavement is designed to have no or very little permeability, with voids contents of 3-8 %. The voids are supposed not to be interconnected; the intention being to protect the road structure from water which can damage it seriously. The latter is what DAC and SMA do. Porous asphalt (or it could equally well be the much more uncommon porous cement concrete) is another asphalt concrete with a very pronounced “gap” gradation, making it porous. For protection of water in the road structure it must be combined with a non-permeable layer below it. Porous asphalt gives much more weight to the coarse (NMA) aggregate, at the expense of the medium aggregate sizes. Furthermore, the smallest aggregates and the sand have a lower contribution. This creates a lot of voids between the largest stones throughout the pavement thickness and with proper proportions the voids may be interconnected. Then the pavement becomes “porous” and can provide drainage of water. The voids and the connection channels between them may have different widths, lengths and shapes, which all affects the water and air draining performance. These are described with certain terms such as air flow resistance and tortuosity. The air flow resistance is the resistance that the air flow is subject to when air is pressed through an open pore. Tortuosity is a somewhat artificial parameter that describes how a pore is shaped. It may not be straight but winding, it may be narrow at some places and widen up at other places.

This has three potentially favorable effects on abrasion and particle emissions:

- (1) It is almost entirely the largest stones (NMA) which are in contact with the tyre tread rubber. There is very little of smaller aggregates that can be crushed or worn off. Since the largest aggregates are supposed to be of very high quality, this decreases road surface abrasion.
- (2) The valleys between the largest stones will be narrower than for SMA as the larger stone can be closer together; this reduces the enveloped road surface profile, so the macrotexture that the tyre tread is contacting becomes lower. This reduces stick-slip movements in the contact patch.
- (3) The valleys in the surface will be deep and connected to the porosity (air voids) in the pavement structure. They can store some of the loosened particles, either permanently or temporarily. If they are stored permanently, it means that they are clogging the air voids, which is unwanted, although it has a favourable effect on some part of the particle emissions. If they store the particles temporarily, the particles can run-off the pavement with rainwater either on the top surface macrotexture or within the porosity with outlet to the roadside. In both cases particles will move slowly in (dirt) water to the roadside and not be emitted in the air widely around the road. This may be enhanced since porous pavements should always have a little higher lateral slope than regular pavements (3 % instead of 2 %), enabling better run-off from the pavement to the roadside. Additionally, in rainy weather the water on the road, mixed with road particles will be splashed and sprayed off the pavement surface by the action of the vehicle tyres and the air turbulence around the vehicles. The heavily loaded truck tyres will suck up water mixed with dirt from the valleys in the surface and even from the voids in it. This makes some of the NEE be moved to the road surroundings mixed with water to a smaller roadside area than when the weather is dry. A disadvantage is of course that the road dirt will be accumulated on roadside objects like road signs, private gardens, vegetation, roadside buildings, etc. But from the NEE and health point of view, this is better than particles spreading widely suspended in the air.

D2.4. Properties and design of road pavements with focus on non-exhaust particle emissions

With regard to the range of NMAS of the porous asphalt, one may consider it as follows:

- 16 mm where noise reduction or rolling resistance are of lower importance than wet skid resistance. For example, the main part of the Dutch national network is paved with PA 16.
- 11 mm where noise reduction or rolling resistance are equally important than wet skid resistance. This is a common gradation of noise-reducing asphalt pavements. For example, it is the main gradation in Swedish porous asphalt and is used in many central and south European countries.
- 8 mm where noise reduction or rolling resistance are very important. This is a common gradation of noise-reducing asphalt pavements, which is used in many central and south European countries.
- 6,3 mm or 4 mm where noise reduction is extremely important. This is not a common gradation of noise-reducing asphalt pavements, but is used in some middle-European countries, more or less on an experimental basis.

Since voids are wider, the larger the NMAS is, which enhances the accumulation or transport of particles in the porosity, for NEE purposes, the larger NMAS would be preferred. To some extent this advantage may be balanced by the lower macrotexture with smaller NMAS, but it is estimated / speculated that the net effect for NEE is better for the larger NMAS. Therefore, in NEEVE, both 11 mm and 16 mm PA are planned for testing.

In NEEVE we will limit our tests to single-layer PA since double-layer PA (DPA) is much more complicated and expensive. However, DPA would have a much higher potential for storing and removing particles through the porosity (voids) system. This is because DPA are usually more than double as thick as single PA which means that there is also more than double as many voids to store and remove the particles. Additionally, it means that it takes a longer time until a DPA is clogged until a PA is clogged. All this is very advantageous for low NEE.

4.5.6. PA 16

The same as for PA 11 applies also for PA 16, with the exceptions discussed above.

4.5.7. OSMA 11 (Open textured SMA)

The European standard for SMA (EN 13108-5) presents a grading specification with very wide tolerances. It means that SMA pavements may differ significantly although produced in formal according to this common standard. A few cases of more open SMAs (but with small additions of rubber or fibres) have appeared to reduce noise by 1-3 dB [Haberl, 2008]. They have a voids content around 10 % when new.

In NEEVE, we want to take the open SMA topic further, by producing an Open-textured SMA (OSMA) which is a hybrid between SMA and PA. It will mean that the relative amount of medium-sized aggregate will be reduced, essentially as much as in a PA. It will become a gap-graded SMA. However, the small aggregate will remain at a relatively high level in order to provide a continued dense pavement with strong connection between the larger aggregates. Its macrotexture will be high as for a normal SMA, but the larger stones will be relatively close to each other and thus create a profile with narrower valleys which is enveloped well by the tyre.

D2.4. Properties and design of road pavements with focus on non-exhaust particle emissions

The gradation with 11 mm NMAS is chosen in order to make it easier to compare with the other pavements; especially of course the SMA 11.

In Japan there is a pavement used by the Japanese motorway pavement company NEXCO which is quite similar to the OSMA 11, which is called “Hybrid Mix” [Kato et al, 2010]. It has such an open texture with narrow and deep valleys that it looks from above the same as a porous asphalt. But it is impervious since there are no interconnecting voids and thus is not subject to clogging. It has become popular in Japan. The acoustic effect is equal to when a PA is clogged [Sandberg, 2021].

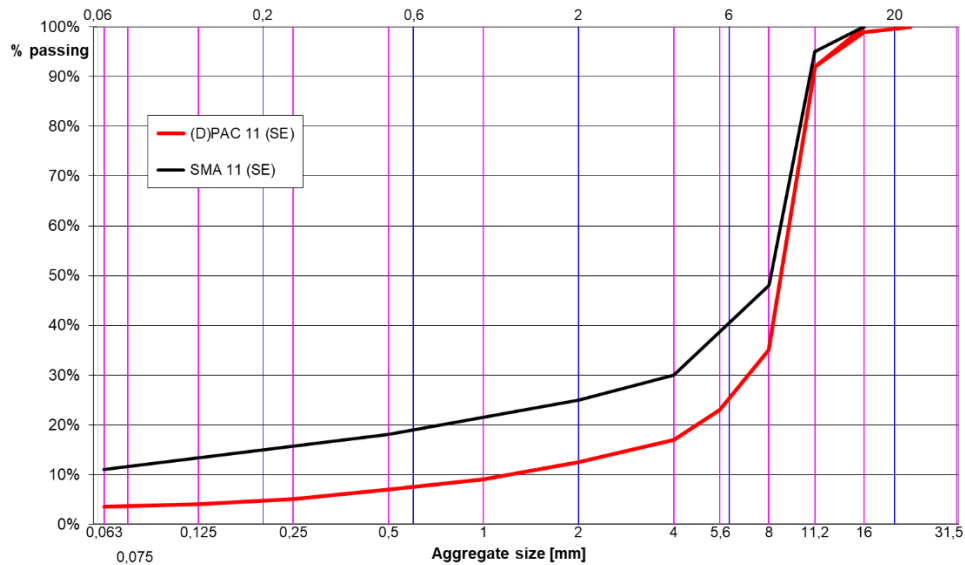


Figure 11. Gradation diagram comparing SMA 11, OSMA 11, PA 11. OSMA will be approx. midway between the two curves.



Figure 12. Surface view of special Hybrid Mix pavement in Matsui in Japan. It looks like a PA but it is actually not permeable

4.5.8. PA 11 with steel slag

There is agreement that a pavement with steel slag should be included in the NEEVE experiments as part of its innovation focus. But exchanging the natural aggregate with steel slag can be done in a range of common asphalt pavements. Two types are interesting since they would be possible to compare with the same pavement with natural aggregate in the project: SMA 11 and PA 11.

VTI has a project in which a double-layer PA 11 is being tested, having steel slag in the top layer (see Figure 13). Its performance in terms of noise and durability was comparable to a similar pavement with natural aggregate on the same road until the age of 6 years [Sandberg, 2023]. The conventional pavement acting as a reference in this case had high-quality aggregate of porphyry (NBM < 5). The NBM value indicates that the aggregate is among the best one can find; see e.g. Figure 1. But presently at the age of 8 years it has a lot of ravelling and is totally clogged. The reference pavement had already been repaved after 6 years for the same reasons.

In Sweden, there is a successful SMA 11 with steel slag in central Linköping, just a few km from the offices of VTI (see Figure 14). That city street is part of a ring road and at this location is exposed to exceptional turning and stop-and-go traffic. In wintertime most tyres there use studs so being in good condition after 10 years is very good. It has performed better in terms of durability than a conventional SMA 11 [Sandberg, 2023].

These results suggest that steel slag may be an alternative to high-quality natural aggregates, superior in durability to, for example, limestone and other common and relatively inexpensive road materials. It is a sad fact that in many countries, high-quality (durable) natural aggregates are becoming expensive and rare. Then, from an environmental point, it is better to use a waste material such as steel slag, of course with consideration of any other environmental hazards. However, the Chinese studies mentioned in Section 3.3.3.1 and in [Sandberg, 2023] have found no serious problems with the steel slag, rather that it is better to have it in a road pavement than leaching unwanted substances in a stockpile. The main disadvantage of steel slag is that it is very heavy to transport as its density is much higher than natural aggregates, which means extra cost. But the transport cost comparison very much depends on where the raw material is located.

Steel slag also has the advantage of always having a dark grey colour throughout its lifetime, which is an advantage for the contrast with road markings.

D2.4. Properties and design of road pavements with focus on non-exhaust particle emissions



Figure 13. Double-layer PA with steel slag aggregate in the top layer on E4 in Huskvarna, Sweden (right lane only). Exposed to high volume of heavy trucks; four years old



Figure 14. SMA 11 with steel slag aggregate on Industrigatan in Linköping, Sweden, 8 years old (the darker parts only). Exposed to high volumes of cars and heavy busses and laid in T-crossings. The pavement still looks good in 2025 at the age of 10 years.

In NEEVE it will be decided in WP3 which pavement that will be the best to make an experiment with, SMA 11 or PA 11. At the moment, a PA 11 is preferred as it will have the additional effect of porous pavements explained above. It is a little more challenging to dimension than an SMA 11, but advice is given in an Annex in [Sandberg, 2023].

D2.4. Properties and design of road pavements with focus on non-exhaust particle emissions

4.5.9. Comparison of the pavement types to be tested

The following table is an attempt to make an expert pre-evaluation of advantages and disadvantages of the pavement types considered for testing. It is of course subjective but gives an indication of the reasons why the pavements are considered. The table may be compared with a similar expert evaluation at the end of the project.

Table 1. Pre-evaluation of the pavement types intended for testing. A + mean a slight advantage, ++ a clear advantage and +++ a significant advantage relative to the reference SMA 11. A minus sign - means a slight disadvantage, -- a clear disadvantage and --- a significant disadvantage relative to the reference SMA 11. A neutral evaluation is indicated as +/-

Performance parameter	SMA 11	SMA 8	PA 11	PA 16	OSMA 11	PA 11 slag
NEE PM2.5	ref	-	+	++	+	+
NEE PM10	ref	-	+	++	+	+
Road abrasion overall	ref	-	+/-	+	+/-	+
Lifetime expected	ref	-	+/-	+	+	+/-
Tyre rubber abrasion	ref	+	+	-	+	+/-
Ravelling resistance	ref	-	+/-	+/-	+/-	+/-
Studded tyre wear	ref	---	-	+/-	+	+/-
Rolling resistance	ref	++	+	+/-	+	+/-
Wet skid resistance	ref	-	+++	+++	+	++
Noise reduction	ref	-	+++	+	++	++
Paving cost per m2	ref	-	--	--	-	---
Proven experience	ref	+	++	+	--	+

4.5.10. Common issues worth considering

When it comes to testing the NEEVE pavements in field applications, it is suggested to consider the lateral slope of the pavements. A common slope is 2 % but for porous pavements a 3 % slope is better to improve water runoff and thus to avoid clogging, or at least to delay clogging. It is suggested that this is used for the PA pavements in NEEVE.

It should be discussed if a higher slope is useful also for the dense pavements as water runoff will be improved and this could also include some particles. It should be a discussion with the road authority in charge of the experimental section(s).

Due to the short duration of NEEVE, we will not be able to test how pavement performance changes with time; it is even too short to do some accelerated tests. Nevertheless, wherever possible within the time frame of NEEVE, performance tests of experimental pavements should be made at least when they are new and another time before NEEVE ends.

In case NEEVE has access to models predicting the performance over time of the pavements, an estimation can be made based on such models, but as some of our test pavements are innovative existing models may not give results with reasonable confidence.

5. Methodology

5.1. Asphalt sample preparation

5.1.1. Introduction

The laboratory preparation of asphalt specimens constitutes a fundamental stage in the experimental framework of this deliverable, as it directly affects the reliability, reproducibility and representativeness of the test results related to non-exhaust emissions (NEE). The selection of materials, formulation procedure, and compaction method have all been defined in alignment with the performance criteria outlined in Chapter 3, where the influence of aggregate quality and binder characteristics on pavement abrasion and PM emissions was extensively discussed.

The section is structured into three main parts, as described as follows. First, the materials used in the asphalt design are presented, including the type and properties of the aggregates and binder selected based on the findings discussed in previous chapters. Then, the mixing protocol is described in detail, outlining the temperature, sequence, and methodology applied to ensure optimal binder distribution and mixture homogeneity. Finally, the compaction process is described, highlighting the need to ensure that the resulting mixtures achieve an adequate texture and density, representative of actual pavement conditions.

In order to guarantee the robustness of the experimental assessment, a total of four specimens were prepared for each pavement solution considered, including both cylindrical and slab samples, as described in Section 5.1.4. This approach ensures the statistical relevance of the results obtained in the various laboratory tests defined in the experimental plan. The dimensions of each specimen type (cylindrical or slab) were selected in accordance with the specific requirements established by the applicable standards for each type of asphalt mixture.

A general overview of the prepared specimens is presented in Figure 15, where both cylindrical and slab samples can be observed after compaction and curing. The image highlights the surface appearance, aggregate distribution, and texture uniformity achieved across the different asphalt mixtures. Visual inspection confirmed the absence of segregation or visible defects, supporting the overall consistency and suitability of the specimens for the subsequent mechanical and emission performance testing.



Figure 15. General overview of different asphalt samples produced during D2.4

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5.1.2. Materials Used

All asphalt mixtures were produced using porphyritic aggregates, selected for their excellent mechanical stability and resistance to degradation under traffic-induced stress. As discussed in Chapter 3.3.1.2, these aggregates are characterised by low fragmentation potential and superior polishing resistance, which have been demonstrated to be particularly critical for Life NEEVE project objective. The mineralogical composition and petrographic texture of the porphyritic material help reduce the generation of fine particles during tyre–pavement interaction, thereby enhancing both environmental and functional performance.

To further justify this selection, a comparative analysis was performed between the porphyritic aggregate and a limestone-based aggregate (both are commonly used in Spain for asphalt pavement construction), focusing on two key mechanical parameters: Los Angeles (LA) abrasion test and Polishing Stone Value (PSV). As shown in Table 2, the porphyritic aggregate exhibited markedly better performance in both parameters, confirming its suitability for high-resistance surface layers.

Table 2. Aggregate mechanical evaluation. Porphyritic – Limestone comparison

Mechanical Test	Standard Test (UNE-EN)	Porphyritic Aggregates	Limestone Aggregates
Los Angeles Abrasion (%)	1097-2	12	24
Polished Stone Value	1097-8	53	45

The binder employed in all asphalt formulations was a PMB 45/80-65 (polymer-modified bitumen), as its grading exhibits a well-balanced combination of high viscosity, resilience, and adhesion, making it particularly effective in reducing binder disintegration and improving resistance to rutting and ravelling. Its polymer structure enhances the flexibility and ageing resistance of the asphalt matrix, which is essential for long-term performance under repeated tyre contact and environmental exposure.

5.1.3. Mixing Protocol

To ensure optimal binder dispersion, aggregate coating, and internal homogeneity within the asphalt mixture, the mixing process was designed as a two-phase sequence, tailored to the rheological characteristics of the polymer-modified bitumen and the granulometric distribution of the aggregates. This approach allows for a more effective integration of the binder with the coarser particles while also facilitating a uniform distribution of the finer fractions and filler materials.

- Initial Phase (Coarse Aggregate Pre-coating). The pre-heated PMB binder was first combined with the coarse aggregate fractions, ensuring full coverage of the structural skeleton of the mix. This step is crucial for guaranteeing aggregate interlock and resistance to load-induced displacement.

D2.4. Properties and design of road pavements with focus on non-exhaust particle emissions

- Final Phase (Incorporation of Fines and Filler). Once a consistent coating of the coarse aggregates was achieved, the fine aggregates and filler materials were introduced gradually into the mixer. This allowed the formation of a cohesive mastic and minimised the risk of segregation. The entire mixing operation was conducted at a uniform temperature of 180 °C, optimised for the handling of PMB binders, as excessively high temperatures may lead to premature oxidation or loss of elasticity.

5.1.4. Compaction Procedure

Once the asphalt mixture was prepared (following the mixing protocol described in the previous section), the compaction process was carried out using two complementary methods, depending on the type of specimen and the intended laboratory tests.

First of all, for slab specimens, a roller compactor was employed in accordance with the standard UNE-EN 12697-33, which enables the production of uniform asphalt plates with controlled bulk density, air void content, and surface texture. These full-size compacted slabs were used for the evaluation of wheel tracking resistance, drainability, and macrotexture via the sand patch test. Additionally, selected slabs were cut into smaller specimens to carry out fatigue resistance tests and to analyse the tyre–pavement interaction.

In parallel, cylindrical specimens were prepared using a gyratory compactor, following the guidelines established in UNE-EN 12697-31. Specifically, these gyratory-compacted specimens were used for the stiffness modulus test and the Cantabro particle loss test, as they provide the necessary consistency and compaction profile required by these mechanical tests.

In summary, the methodology applied for the preparation of asphalt specimens ensures a high degree of reproducibility, structural integrity, and representativeness with respect to real-world pavement conditions. The combined selection of mechanically robust aggregates, polymer-modified binder, and a controlled two-phase mixing and compaction process establishes a consistent experimental baseline for evaluating the influence of pavement design on non-exhaust particle emissions in subsequent laboratory testing.

5.2. Potential laboratory test methods

Several standardised laboratory tests are commonly used to characterise the abrasion, fragmentation and polishing resistance of aggregates. Here are four methods which are based on exposing the material to rotation in a steel drum together with solid balls (by steel) which will hit the material. The result will be the abraded material after the exposure in % of the total exposed mass:

- Nordic Ball Mill (NBM) test (EN 1097-9), widely used in Nordic countries, evaluates abrasion resistance under simulated studded tyre conditions. Lower NBM values (depending on the nature of the aggregates) indicate lower mass concentrations of PM10 particles in the total abraded material.

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- Los Angeles (LA) abrasion test (EN 1097-2) assesses the resistance to impact and grinding action, typically applied to those aggregates used in high-traffic intensity pavements. In this case, it is difficult to establish a strong relationship between Polished Stone Value (PSV) and the concentration of PM₁₀ in total abraded material, but it can be observed that higher PSV values usually tend to have lower PM₁₀ mass concentration.
- The Cantabro test (EN 12697-17:2017). This is similar to the LA abrasion test except that instead of putting loose unbound aggregate in the drum, entire pieces of bound material (typically 100 mm diameter) are subject to the rotation and hitting by balls. It is considered as especially useful for testing small variations in construction of porous asphalt [Ghafoori, 2022].
- Micro-Deval test (EN 1097-1) measures the resistance to wear under wet conditions and rotational movement, providing a good indicator of aggregate breakdown in the presence of water and mechanical stress. It is similar to the LA abrasion test, except that water is added to the aggregate in the drum.
- The Prall test (EN 12697-16:2004), is normally used for evaluating dense graded asphalt mixtures; it has also been used for evaluating other type of mixtures such as PAs for determining their wearing resistance. It can provide useful information about the adhesion/cohesion and also quality of the mineral aggregates under tough moisture and loading conditions [Ghafoori, 2022].

These tests yield complementary data, and their results are often used in combination when specifying aggregates for high-performance asphalt mixtures. Studies have shown strong correlations between these test values and observed PM₁₀ emissions in pavement wear simulations, confirming that aggregates with lower abrasion indices tend to produce fewer airborne particles. See further Section 3.3.2.1.

There is another test worth mentioning, namely the Scuffing test:

- Resistance to scuffing (CEN/TS 12697-50:2018). This is a test method applied to flat asphalt slabs for determining the resistance to scuffing of asphalt mixtures which are used in surface layers and are loaded with high shear stresses in the contact area between tyre and pavement surface which can be caused by cornering of the vehicle. Due to these shear stresses, material loss will occur at the surface of these layers. The test is normally performed on asphalt layers with a high amount of air voids (e.g. porous asphalt), but can also be applied on other asphaltic mixtures. Test specimens are used either produced in a laboratory or cut from the pavement. Porous asphalt is especially sensitive to excessive longitudinal and lateral (side) forces.

5.3. Laboratory plan

The laboratory plan established for the LIFE NEEVE project has been designed to evaluate the influence of asphalt pavement design on the generation of non-exhaust emissions (NEE), with particular emphasis on particles generated through tyre–pavement interaction. This plan is a central component of the experimental work described in this deliverable and supports the project’s broader goal of identifying and promoting low-emission, high-durability asphalt solutions.

The objective of the laboratory plan is to characterise the mechanical, surface and environmental performance of a set of asphalt mixtures specifically designed or selected for their relevance to NEE dynamics. The analysis focuses on evaluating how differences in aggregate type and size, binder formulation, and mixture texture influence properties directly related to abrasion resistance, particle detachment, and surface degradation.

Each asphalt configuration corresponds to a working hypothesis, previously defined based on literature review, existing standards, and partner expertise. These hypotheses cover a diverse range of aggregate gradations, surface textures and void contents, allowing for a comparative analysis of their influence on wear-related phenomena and particle release.

- SMA 11 (reference Stone Mastic Asphalt)
- PA 11 and PA 16 (Porous Asphalt, single layers)
- OSMA 11 (Open – Textured SMA)
- SMA 8 (variant with reduced maximum aggregate size)

The methodology applied follows a three-stage sequence: specimen fabrication, material characterisation, and abrasion behaviour evaluation. Each of these stages has been carefully aligned with European standards procedures, ensuring both the scientific validity and practical applicability of the results.

Initially, as described in the previous section, the asphalt samples were produced using high-quality porphyritic aggregates and a polymer-modified bitumen (PMB 45/80-65). The fabrication process was carried out using a controlled two-phase mixing protocol, followed by compaction through slab moulding according to UNE-EN 12697-33. This procedure enabled the production of homogeneous plates with controlled bulk density and surface texture, closely replicating the characteristics of in-service pavements. These slabs served as the basis for extracting prismatic or plate-based specimens used in surface, texture, and friction testing.

In parallel, and with the objective of assessing the mechanical performance of each asphalt mixture under load, a second set of specimens was prepared in the form of cylinders using a gyratory compactor. This process followed the specifications laid out in UNE-EN 12697-31, which defines the procedure for manufacturing test specimens by gyratory compaction for the determination of properties such as stiffness, fatigue resistance, and resistance to permanent deformation. This method ensures the reproducibility of compaction conditions and the internal consistency of the specimens. All samples were validated prior to testing in terms of bulk density, air void content, and compaction homogeneity, ensuring the comparability and technical robustness of the results across all tested asphalt configurations.

5.4. Laboratory test methods used in the Task

Once fabricated, the asphalt specimens were subjected to a comprehensive set of laboratory tests, in order to fully evaluate the performance of each asphalt configuration from both a mechanical and surface interaction standpoint. These tests are aligned with European standards and specifically selected to characterise the properties most relevant to wear resistance, particle loss, and surface functionality in the context of NEE. The tests performed include:

- Mechanical performance analysis:
 - Stiffness Modulus (N 12697-26). This test assesses the elastic response of asphalt mixtures under load, providing an indication of the pavement's ability to resist deformation. A stiffer mixture tends to deform less under traffic, potentially reducing surface wear and associated particle release.
 - Wheel Tracking (EN 12697-22). This test simulates rutting under repeated load cycles, allowing the evaluation of a pavement's resistance to permanent deformation. Pavements with lower rut depths are more likely to maintain their texture and structural integrity over time.
 - Fatigue Resistance (EN 12697-24). This test evaluates the resistance of the asphalt mixture to cracking under cyclic loading. High fatigue performance ensures that the surface remains intact under repeated tyre passes, reducing the risk of material detachment.
- Asphalt texture analysis. The macrotexture of the asphalt surface was measured using the Sand Patch Method, commonly referred to as the circular sand patch test. This technique is particularly effective for assessing the quality of surface finishing, as well as for identifying differences in void distribution and texture consistency across the various asphalt mixtures. The macrotexture was quantified by calculating the Mean Texture Depth (MTD), which provides a representative value of the surface roughness relevant to tyre–pavement interaction and potential particle retention
- Drainability (EN 12697-40). This test determines the permeability of porous asphalt mixtures by quantifying water drainage capacity.
- Friction Pendulum Test (EN 13036-4): This test measures the surface skid resistance by simulating the tyre–pavement interaction at micro-scale. It is mainly sensitive to the microtexture of the aggregates. It is relevant to skid resistance only at low water depths and low or medium speeds as it has a poor relation to macrotexture.
- Cantabro Test (EN 12697-17:2017). This test evaluates the particle loss resistance of asphalt mixtures by exposing compacted specimens (as defined in Chapter 5.1.4) to rotational abrasion. The mass loss recorded is directly interpreted as a measure of the mixture's cohesion and its tendency to generate loose particles. The Cantabro test is generally considered as suitable especially for open-graded asphalt pavements, as OSMA-11 designed during this task.

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In a further step, to analyse the interaction between the asphalt surface and traffic conditions, a modification of the Accelerated Polishing Machine was used to recreate the tyre-pavement contact dynamics in a laboratory basis. This approach allows for a more realistic simulation of surface wear processes, being able to determine the temperature (see Figure 16) or the total amount of particle loss during the trial test.

For these tests, cut slabs obtained from the compacted plates (previously described in earlier sections) were used as the base specimens. This selection ensures that the surface texture and structural integrity are representative of real pavement layers. It is important to highlight, however, that due to the inherent complexity and novelty of simulating tyre-pavement interaction in a reproducible and scalable way, both the equipment adaptation and methodological development will continue to be refined as part of the activities planned under Work Package 3.



Figure 16. Accelerated Polishing Machine adaptation to analyse the asphalt-tyre interaction

All laboratory procedures were carried out under strictly controlled measures, including environmental conditioning, equipment calibration and test replication, ensuring that all results obtained are both robust and comparable across mixtures. Any atypical results or procedural inconsistencies were systematically identified, recorded and incorporated into the analysis to ensure the integrity and traceability of the experimental outcomes.

Overall, the laboratory plan implemented offers a rigorous and standardised methodology for characterising the behaviour of asphalt pavements in relation to NEE. The insights generated from this controlled phase of the project provide a solid technical foundation for selecting the most promising low-emission mixtures. These will subsequently be evaluated in real-world pilot conditions, enabling the validation of their performance under representative traffic and environmental scenarios within the next stages of the LIFE NEEVE project.

5.5. NEE analysis. Asphalt pavement contribution

Within the broader framework of the LIFE NEEVE project, the contribution of asphalt pavement to NEE is recognised as one of the key factors influencing the generation and mobilisation of particulate matter (PM) in urban environments. As described in Deliverable 2.2, NEE originates from multiple interrelated mechanisms, including tyre wear, brake wear, and road surface abrasion, with pavement-related emissions playing a fundamental role due to both mechanical detachment and dust resuspension processes.

In order to isolate and quantify the specific influence of asphalt surfaces, the project has adopted a combined approach based on controlled laboratory characterisation (as detailed in Chapter 5.3) and experimental setups designed to simulate particle release under realistic conditions. Although field quantification is scheduled for future phases, Deliverable 2.2 lays the groundwork for this analysis by identifying the relevant emission pathways and proposing a classification of source-specific contributions.

The methodology proposed relies on the use of a dedicated chamber system capable of enclosing specific vehicle-pavement interactions and capturing airborne PM released from the contact interface. In this configuration, abrasion between the tyre and the asphalt surface is simulated under variable loading and rolling conditions. These simulations are designed to reflect both typical driving dynamics (acceleration, deceleration, constant speed) and textural differences between pavement types. The instrumental setup, described in D2.2, includes high-resolution PM monitoring equipment capable of detecting PM₁₀ and PM_{2.5} fractions, with sampling points strategically located at tyre height to capture representative emissions.

Furthermore, the experimental design accounts for the effect of pavement macrotexture, aggregate type, and binder performance. Particularly, it is hypothesised that mixtures with coarser macrotexture and lower polishing resistance are more prone to generating loose particulate matter, which may be resuspended by tyre movement or released during abrasion events.

Although definitive quantification of asphalt-derived NEE is pending the implementation of the full testing protocol, the preliminary results from laboratory abrasion tests and texture evolution (see Section 5.4) provide indirect indicators of the relative emission potential of each pavement configuration. This includes data from polishing resistance, and Cantabro particle loss tests, all of which contribute to establishing a relative ranking of mixtures in terms of their expected contribution to PM generation.

Ultimately, the integration of this characterisation results with the experimental framework defined in Deliverable 2.2 will allow the project to develop correlative models linking pavement design parameters to measured PM concentrations, supporting the development of decision tools and regulatory recommendations aimed at minimising NEE from urban road infrastructure.

6. Results

6.1. Asphalt Volumetric Characteristics. Grading Curves

6.1.1. SMA 11

As described in previous sections of this document, an SMA 11 asphalt mixture has been selected as a reference solution among the different sets of asphalt types evaluated in the LIFE NEEVE project, as it is widely implemented across Europe and recognised for its robustness under high traffic loads. SMA mixtures are defined by their gap-graded aggregate structure, where a coarse stone skeleton is stabilised with a binder-rich mastic, providing both mechanical strength and long-term durability. Within the scope of NEEVE, SMA 11 serves as a baseline against which alternative pavement types can be compared in terms of texture, mechanical performance, and potential non-exhaust emissions (NEE).

The grain size distribution obtained for the SMA 11 test sample, shown in Figure 17, confirms the expected gap-graded profile, characteristic of SMA-type mixtures. The curve displays a concentration of coarse aggregates between 4 mm and 11 mm, with a clear reduction in intermediate sizes, which optimises load distribution and enhances rutting resistance.

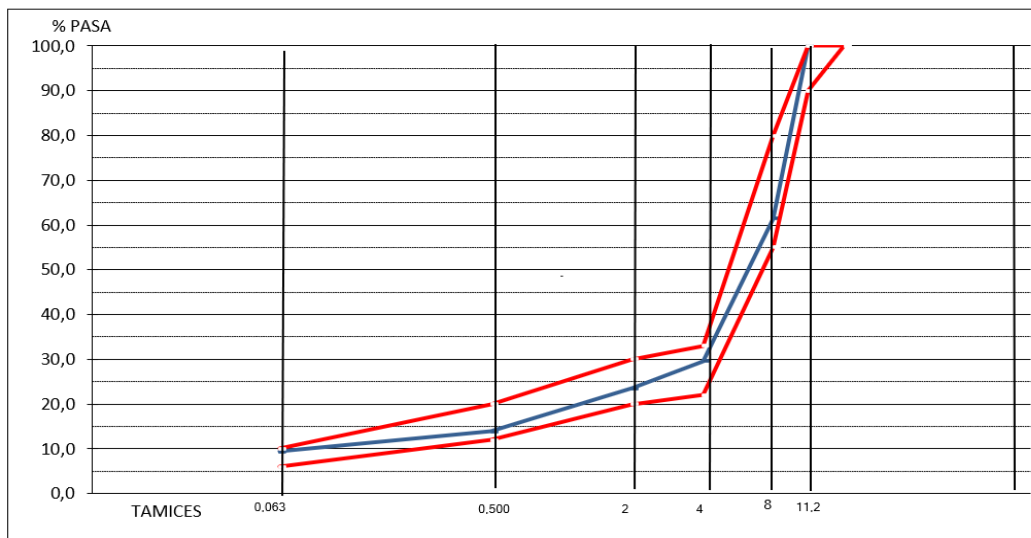


Figure 17. Grading curve (in blue) as prepared for the SMA 11. Note that the red curves in this and the following diagrams are the tolerance limits according to the Spanish standard

The grading curve of this reference mixture was obtained in accordance with the UNE-EN 933-1 standard. The results are also presented in the following table (Table 3):

Table 3. Aggregates sieve analysis (SMA 11)

Sieve Number	11.2	8	4	2	0.50	0.063
% Passing Aggregates	100.0	61.5	29.6	23.5	13.8	9.2

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According to Table 4, laboratory analysis of volumetric characteristics indicates that the SMA 11 mixture meets key performance criteria. The measured air void content falls within the optimal range (typically 3–6 %) and the bitumen content allows to fully coat the aggregate particles while preventing bleeding, which is crucial for long-term cohesion and surface stability. Additionally, bulk density and Marshall stability values confirm good compaction levels and mechanical robustness under traffic loads.

Table 4. Volumetric characteristics (SMA 11)

Bitumen content (%)	5.90
Void content (%)	5.10
Bulk density (kg/m³)	2,615

Finally, photographic documentation of the compacted samples (illustrated in Figure 18), provides a visual confirmation of the material’s structural integrity. The top surface shows a rough, textured finish typical of SMA mixtures, with exposed coarse aggregates contributing to macrotexture and tyre-pavement friction. The cross-sectional image reveals a well-distributed internal void structure, free from visible segregation, interconnected pores or large internal gaps.

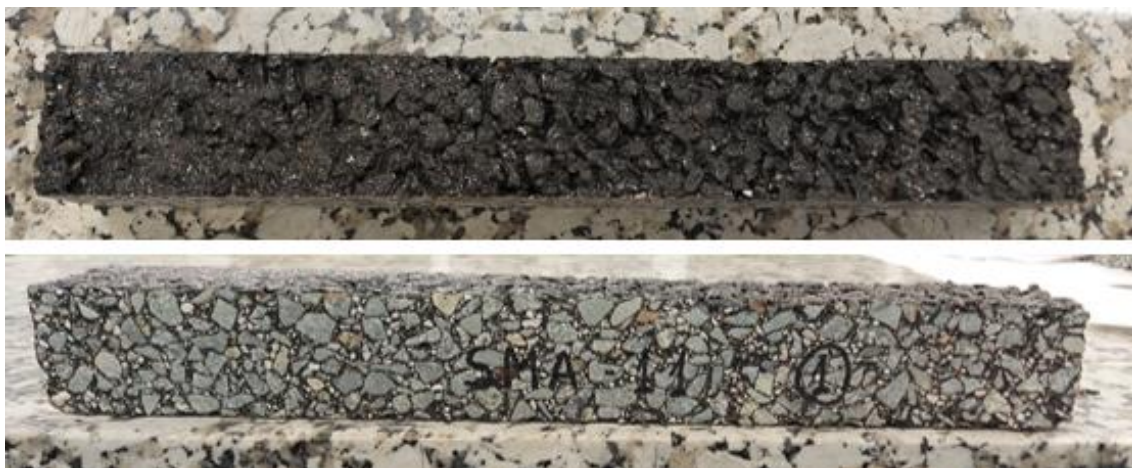


Figure 18. Surface and internal appearance of SMA 11

6.1.2. PA 11

The PA 11 mixture corresponds to a porous asphalt configuration with a nominal maximum aggregate size of 11 mm. This pavement type is characterised by its open-graded structure, favouring high air void content and interconnected porosity throughout the mix. PA mixtures are primarily used in applications where enhanced surface drainage, noise reduction, or dust entrapment are desired. Within the LIFE NEEVE framework, PA 11 is evaluated not only for its mechanical performance but also for its potential contribution to reducing resuspended particulate emissions, owing to its dust-retaining capacity.

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The grain size distribution shown in Figure 19 confirms a typical open-graded profile, with a predominance of coarse aggregates and a significant reduction in fine and intermediate fractions. This gradation ensures the development of a continuous void network, essential for the permeability and acoustic benefits associated with porous asphalt.

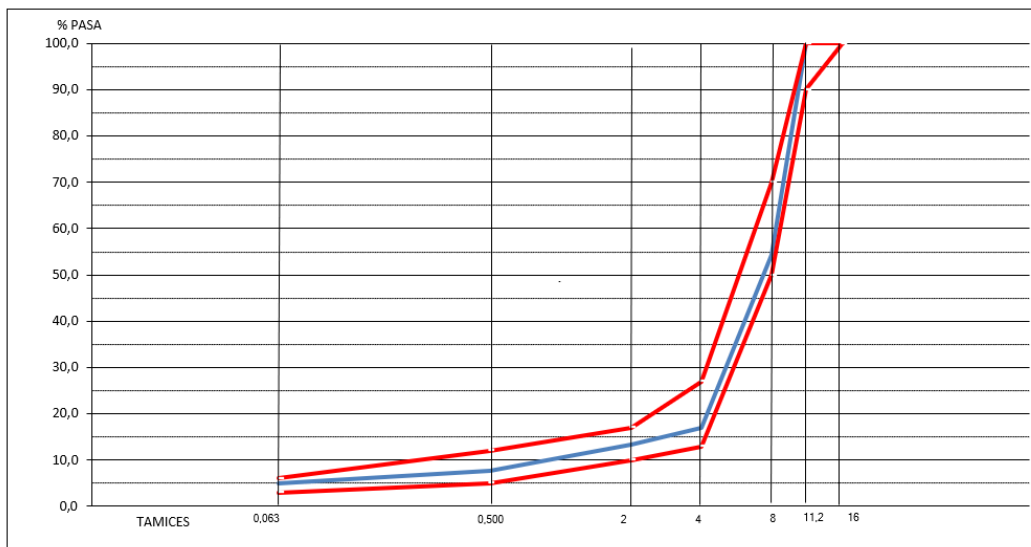


Figure 19. Grading curve as prepared for the PA 11

The grading curve of this mixture was obtained in accordance with the UNE-EN 933-1 standard. The corresponding results are also summarised in Table 5.

Table 5. Aggregates sieve analysis (PA 11)

Sieve Number	11.2	8	4	2	0.50	0.063
% Passing Aggregates	100.0	54.3	17.0	13.3	7.7	5.1

According to Table 6, the PA 11 mixture exhibits a high void content (typically above 18 %), as expected from its design. The bitumen content remains sufficient to coat the coarse aggregate skeleton while allowing void connectivity. The relatively lower bulk density, compared to SMA-type mixtures, reflects the high air void structure. These characteristics support the intended permeability and indicate a strong potential for reduced PM resuspension through dust capture within the voids.

Table 6. Volumetric characteristics (PA 11)

Bitumen content (%)	4.80
Void content (%)	20.20
Bulk density (kg/m3)	2,172

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Finally, the photographic documentation of the compacted sample (Figure 20) clearly shows the open texture and surface roughness associated with porous asphalt. In the cross-sectional view, the interconnected void structure is evident, supporting the expected permeability and demonstrating uniform aggregate distribution and structural integrity.

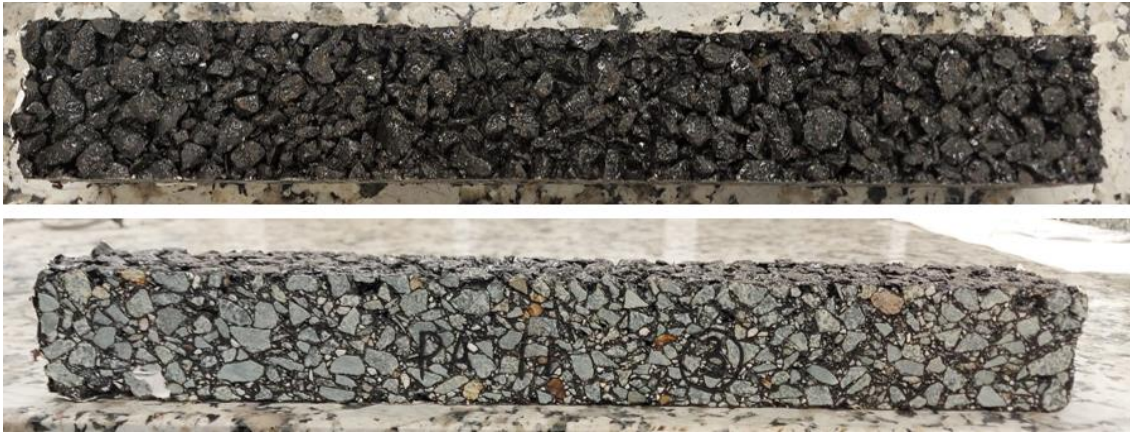


Figure 20. Surface and internal appearance of PA 11

6.1.3. OSMA 11

The OSMA 11 represents an intermediate design approach between conventional SMA and PA asphalt solutions. This formulation was specifically developed within the LIFE NEEVE project to explore the potential of combining the mechanical durability and binder-rich structure of SMA with the enhanced permeability and dust-retention capacity typical of PA mixtures. The idea is to assess whether an optimised gradation, strategically positioned between the SMA 11 and PA 11 configurations, can deliver favourable performance in terms of both structural resilience and non-exhaust emission (NEE) mitigation (see further the justifications in .

As illustrated in Figure 21, the grading curve of OSMA 11 is deliberately positioned between the upper and lower envelopes defined by the SMA 11 and PA 11 curves, respectively. The curve exhibits a reduced content of medium aggregate fractions (typically passing through the 4 mm to 2 mm sieves) resulting in a more open-textured surface than standard SMA, but denser than a fully porous PA. This specific aggregate distribution is not arbitrary, as the reduction of intermediate sizes is key to encouraging the formation of interconnected voids, without compromising structural integrity or leading to binder drainage issues.

This intermediate position in the granulometric spectrum enables OSMA 11 to potentially inherit the mechanical robustness and durability of SMA (due to the presence of a stone-on-stone skeleton and sufficient binder content), while gaining some of the functional benefits of PA, such as increased macrotexture and potential reduction in dust resuspension through partial dust entrapment.

D2.4. Properties and design of road pavements with focus on non-exhaust particle emissions

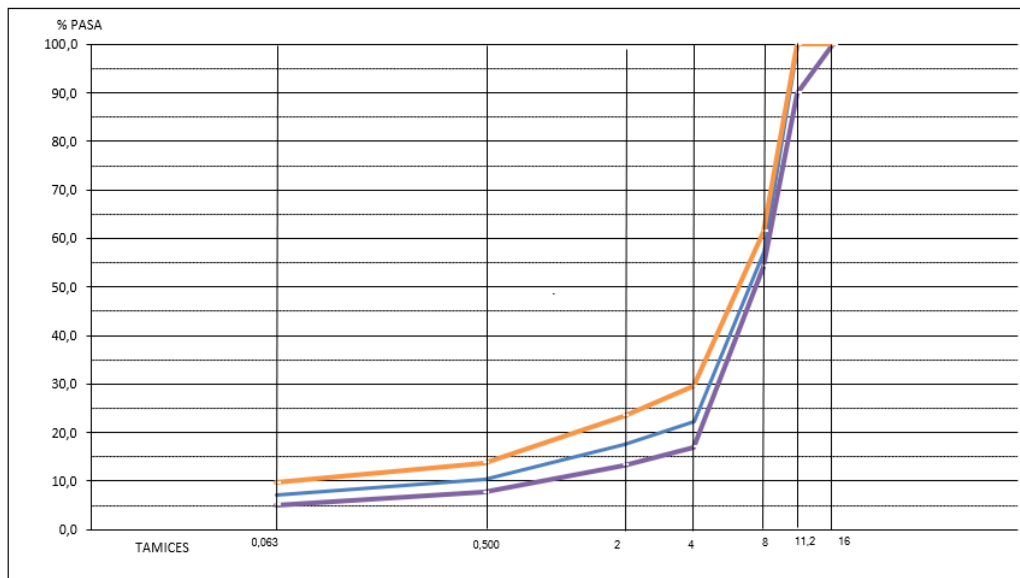


Figure 21. Grading curve as prepared for the OSMA 11. The orange and violet curves are tolerances set by the author (purple as the PA-11 and orange as the SMA-11)

The grading curve was established in accordance with UNE-EN 933-1, and the results of the sieve analysis are presented also in Table 7.

Table 7. Aggregates sieve analysis (OSMA 11)

Sieve Number	11.2	8	4	2	0.50	0.063
% Passing Aggregates	100.0	57.3	22.4	17.7	10.4	7.1

Table 8 summarises the volumetric properties of the OSMA 11 mixture. As expected, the air void content is higher than that of SMA 11, reflecting the reduced presence of medium aggregates and resulting in a coarser texture and increased permeability. At the same time, the bitumen content and bulk density values remain close to those of SMA-type designs, ensuring that the mixture retains mechanical cohesion and compaction quality.

Table 8. Volumetric characteristics (OSMA 11)

Bitumen content (%)	5.40
Void content (%)	12.60
Bulk density (kg/m ³)	2,422

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The external appearance of this sample confirms (Figure 22) the intermediate nature of the surface texture, by having more openness than a conventional SMA 11 (clearly visible voids between the coarse aggregates, but not as pronounced as a PA 11). On the other hand, cross-sectional views highlight a balanced internal structure with sufficient inter-particle contact, alongside open areas that may support water drainage or particulate capture.



Figure 22. Surface and internal appearance of OSMA 11

In summary, OSMA 11 stands as a hybrid alternative aimed at integrating the best attributes of SMA and PA mixtures. Its grading curve and volumetric properties suggest a promising compromise: enhanced texture and reduced potential for particle resuspension, without a substantial sacrifice in mechanical durability. This makes it a strong candidate for use in urban environments where both performance and air quality are key concerns.

6.1.4. SMA 8

The SMA 8 mixture is a finer version of the standard SMA configuration, with a nominal maximum aggregate size of 8 mm. This reduction in aggregate size aims to enhance surface uniformity and potentially improve rolling resistance and tyre-pavement contact area. Within the LIFE NEEVE testing framework, SMA 8 is included to assess how smaller NMAS affects both mechanical performance and the generation of non-exhaust particle emissions. The reason is that there is a trend for using smaller NMAS in order to reduce rolling resistance and noise and it would be good to know if this influences particle emissions negatively.

Figure 23 displays the grain size distribution obtained for this particular solution, showing a gap-graded structure with a shift toward finer fraction compared to the SMA 11 used as reference hypothesis in this project. Additionally, the grading curve was obtained following UNE-EN 933-1 standards, as detailed in Table 9 (same grading as in the figure).

D2.4. Properties and design of road pavements with focus on non-exhaust particle emissions

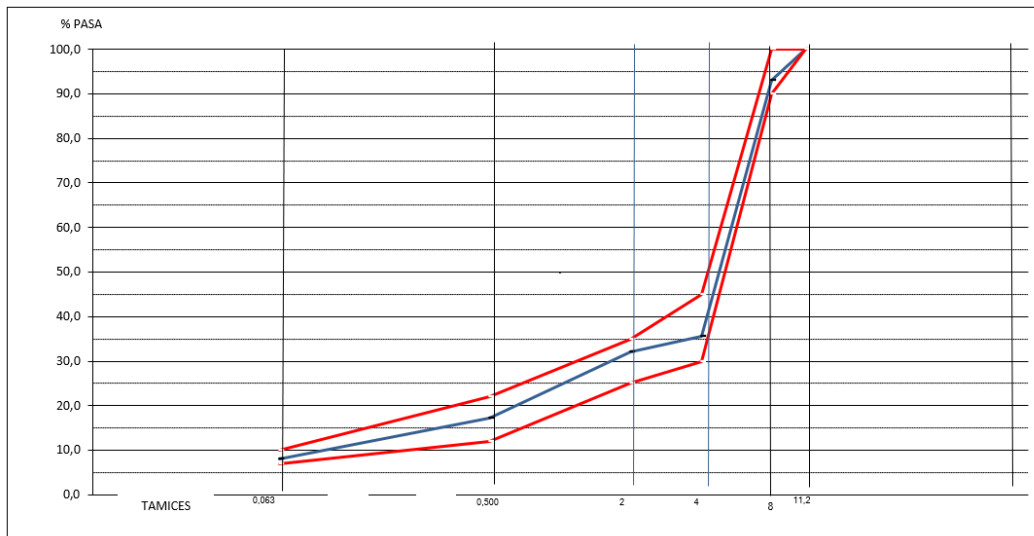


Figure 23. Grading curve as prepared for the SMA 8

Table 9. Aggregates sieve analysis (SMA 8)

Sieve Number	11.2	8	4	2	0.50	0.063
% Passing Aggregates	100.0	93.0	35.6	32.0	17.2	8.1

Table 10 presents the volumetric properties of this asphalt mixture. In this case, the air void and bitumen content indicate that this is a dense mixture, in which the smaller aggregate size may offer benefits in noise, ride comfort and energy consumption but could potentially increase wear, especially under studded tyre conditions (parameter that must be confirmed during upcoming tasks of this project).

Table 10. Volumetric characteristics (SMA 8)

Bitumen content (%)	5.50
Void content (%)	5.30
Bulk density (kg/m ³)	2,628

Finally, the visual inspection of this solution (Figure 24) highlights a denser surface finish compared to SMA 11, with reduced macrotexture but uniform aggregate dispersion, whereas the internal section shows a tightly packed structure with good cohesion.

D2.4. Properties and design of road pavements with focus on non-exhaust particle emissions



Figure 24. Surface and internal appearance of SMA 8

6.1.5. PA 16

Finally, the PA 16 consist of an asphalt mixture solution with a larger nominal aggregate size than the reference samples considered in this project (16 instead of 11 mm), aiming to provide a coarser texture and higher interconnected void ratio. This configuration enhances permeability and surface drainage, especially under high rainfall conditions, and may also reduce particle resuspension due to its increased capacity to trap dust. As shown in Figure 25, the grading curve confirms a typical open-graded profile, with a predominance of coarse aggregates and very limited fines.

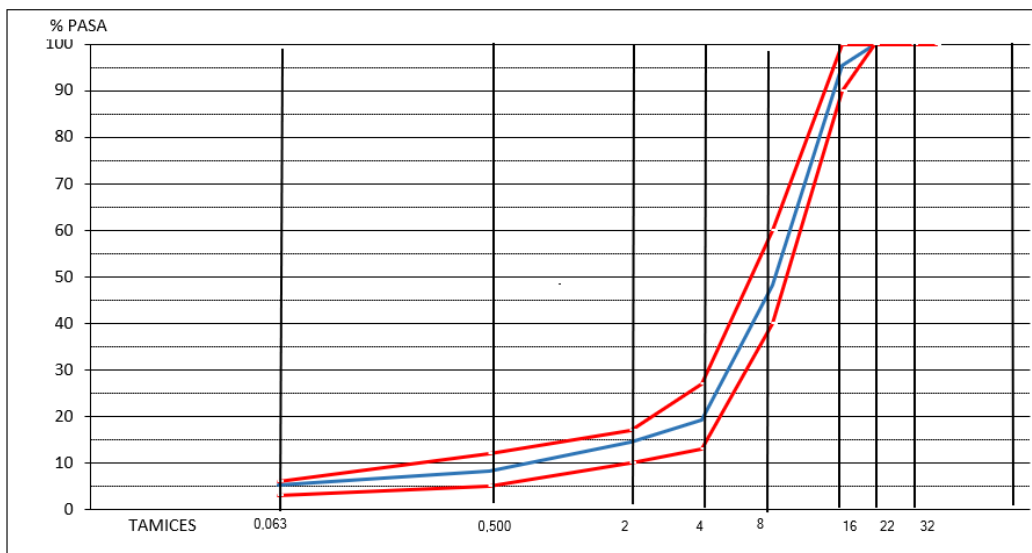


Figure 25. Grading curve as prepared for PA 16

This grading curve has been developed based on UNE-EN 933-1 standards, with results provided in Table 11 (same as in the figure).

D2.4. Properties and design of road pavements with focus on non-exhaust particle emissions

Table 11. Aggregates sieve analysis (PA 16)

Sieve Number	22	16	8	4	2	0.50	0.063
% Passing Aggregates	100.0	95.4	48.3	19.2	14.5	8.1	5.2

The volumetric analysis of this PA 16 hypothesis, outlined in Table 12, shows that the air void content exceeds 20 %, in line with its design purpose. Consequently, the bulk density is relatively low, in comparison with some conventional asphalt samples.

Table 12. Volumetric characteristics (PA 16)

Bitumen content (%)	5.22
Void content (%)	22.40
Bulk density (kg/m3)	2,278

Finally, photographic evidence (Figure 26) shows a highly open surface texture with exposed large aggregates. The cross-sectional image reflects a visibly porous internal network, ideal for drainage but requiring periodic cleaning to maintain performance over time.

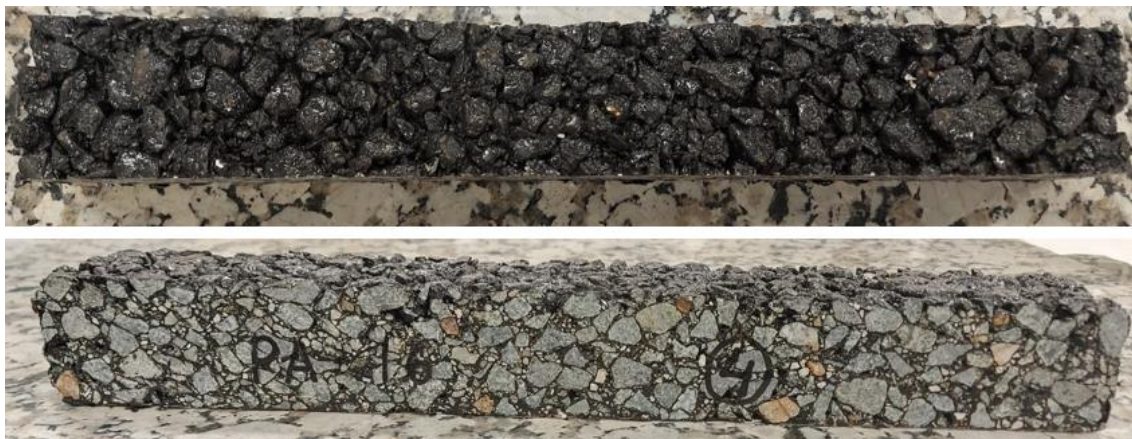


Figure 26. Surface and internal appearance of PA 16

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6.2. Texture Analysis

As stated through this document, pavement surface macrotexture is a critical parameter influencing tyre-road interaction, with direct implications for both safety and environmental performance. In the context of the LIFE NEEVE project, macrotexture is particularly relevant due to its potential effect on NEE, as it influences both the resuspension and entrapment of particulate matter generated at the tyre-pavement interface.

In this study, macrotexture has been quantified through the Mean Texture Depth (MTD), determined using the Volumetric Patch Method. This technique, as illustrated in Figure 27, involves spreading a defined volume of fine sand over the asphalt surface and measuring the average diameter of the circular patch formed, from which the MTD is calculated.

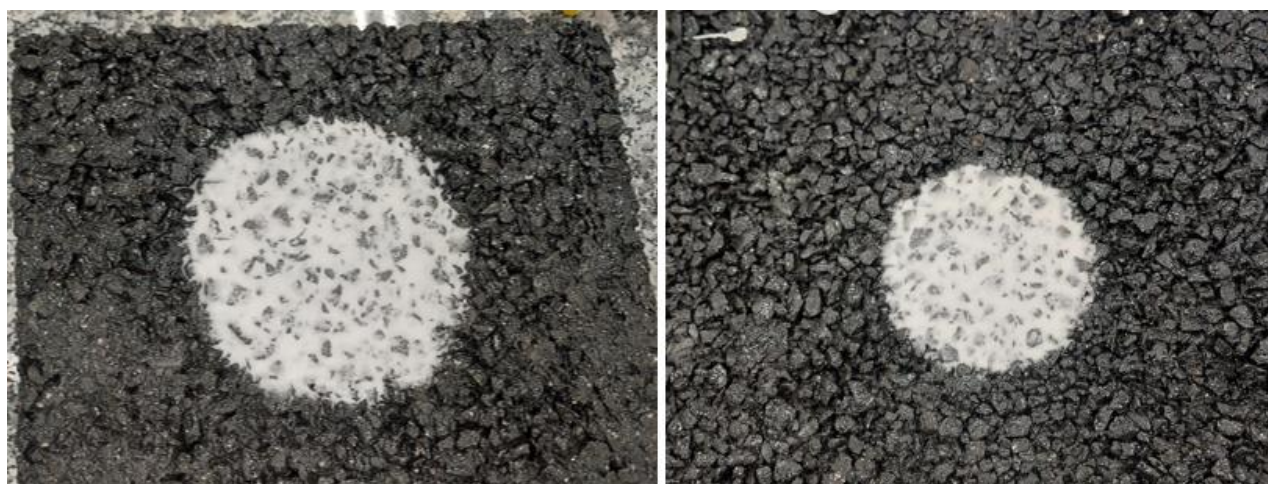


Figure 27. Pavement surface macrotexture. Example of SMA 11 (left) and OSMA 11 (right)

The results obtained are summarised in the following table (Table 13):

Table 13. Pavement surface macrotexture analysis. Volumetric patch technique

Asphalt sample	Measurement 1 (mm)	Measurement 2 (mm)	Medium Value (mm)	MTD/mm
SMA 11	145	135	140	1.6
PA 11	100	110	105	2.9
OSMA 11	110	135	123	2.1
SMA 8	170	170	170	1.1
PA 16	100	105	103	3.0

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As expected, porous asphalt configurations (PA 11 and PA 16) exhibited the highest MTD values, reflecting their open-graded aggregate structure and coarse surface finish. This high macrotexture may facilitate better water drainage and may contribute to capturing road dust, potentially reducing resuspension under dry conditions.

The OSMA 11 solution yielded intermediate MTD values (2.1 mm), consistent with its hybrid nature (sharing characteristics of both SMA and PA mixtures). The reduced presence of medium-sized aggregates in OSMA 11 leads to a coarser surface than SMA 11, yet without the full porosity of a PA. This intermediate macrotexture may offer a balanced response in terms of particle retention and surface durability.

The SMA 11 and SMA 8 mixtures showed lower MTD values, in line with their denser textures and more continuous aggregate skeletons. These lower macrotexture profiles are generally associated with improved rolling resistance and acoustic comfort, although they may be less effective in preventing particle detachment from the surface.

Overall, the MTD results provide important insight into how surface texture varies across asphalt types and how this may influence NEE behaviour. The integration of these findings with profilometry data and functional emission testing will allow for a more complete understanding of the environmental performance of each pavement configuration.

6.3. Drainage capacity

Drainage capacity is a fundamental parameter when evaluating porous asphalt mixtures, as it directly affects both the hydraulic behaviour of the pavement and its potential influence on NEE. To characterise this property, the drainability test was performed in accordance with the UNE-EN 12697-40 standard. The method quantifies two key parameters:

- Drainage time: the time required for a known volume of water to pass through a compacted asphalt slab.
- Hydraulic conductivity (k): this parameter is an indicator of the permeability of the asphalt mixture, expressed in m/s.

As shown in Table 14, this test was considered only in those asphalt configuration designed to be permeable (PA 11, OSMA 11 and PA 16), since dense configurations (SMA 11 and SMA 8) are assumed to be impermeable and, consequently, not suitable for this kind of assessment. The results obtained are presented as follows:

Table 14. Asphalt drainability (UNE-EN 12697-40)

Asphalt Hypothesis	Drainage time (seconds)	Hydraulic conductivity (k)
PA 11	37.7	0.0286
OSMA 11	85.5	0.0126
PA 16	33.0	0.0325

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As expected, PA 16 and PA 11 exhibited the highest drainage capacity, reflecting their open-graded structures and high void connectivity. OSMA 11, with its intermediate grading, showed a more moderate permeability, confirming its role as a hybrid solution that combines some drainage functionality with greater structural cohesion.

6.4. Friction Analysis

Surface friction is a key functional characteristic of asphalt pavements, directly affecting road safety and influencing the tyre – pavement interaction mechanisms. To quantify this parameter, the Friction Pendulum Test was performed following the UNE-EN 13036-4 standard.

This test simulates the tyre–surface contact by measuring the resistance offered by the pavement to a swinging rubber slider, providing an index value known as the Skid Resistance Value (SRV), also known as the British Pendulum Value (BPN). The higher the SRV, the greater the micro-scale friction of the pavement. Table 15 presents the results obtained for each asphalt sample.

Table 15. Asphalt friction analysis. Pendulum test applied 8 times (UNE-EN 13036-4)

Asphalt Hypothesis	Measurement								FINAL
	1	2	3	4	5	6	7	8	
SMA 11	70	65	63	60	59	60	60	59	62
PA 11	65	64	62	60	60	60	59	60	61
OSMA 11	64	62	59	57	57	56	56	56	58
SMA 8	73	71	69	70	69	68	67	65	69
PA 16	72	69	71	66	66	64	63	63	67

The friction results reveal a range of performance across the tested mixtures, with SMA 8 and PA 16 showing the highest skid resistance values, followed by SMA 11 and PA 11 at intermediate levels, and OSMA 11 exhibiting the lowest SRV. These variations reflect differences in surface texture, aggregate gradation, and openness, all of which influence the degree of tyre-pavement interaction and resulting grip.

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6.5. Particle Loss (Cantabro Test)

The degree of aggregate wear can be indirectly assessed through the Los Angeles Abrasion Test, performed in accordance with UNE-EN 1097-2, which simulates the effects of surface attrition and tyre/road impact. This standardised method evaluates the percentage of mass loss of an asphalt sample subjected to rotational tumbling with steel spheres, providing a quantitative index of their susceptibility to wear. Figure 28 illustrates the external appearance of some of these asphalt samples after the Cantabro test, in which particle loss can clearly be seen.



Figure 28. Example of the appearance of the asphalt samples after the Cantabro test

In this context, Table 16 shows the main results obtained for each sample, by measuring the percentage of mass loss after the test. As seen in the table, SMA 8 and SMA 11 display the lowest abrasion values, confirming their good mechanical integrity and the high resistance of their aggregate skeletons to fragmentation. In contrast, PA 16 and PA 11 exhibit higher wear values, reflecting a greater susceptibility to surface degradation due to their open-graded and more fragile matrix. OSMA 11, as an intermediate formulation, shows a moderate abrasion rate that aligns with its hybrid design.

Table 16. Asphalt particle loss analysis. Cantabro test (UNE-EN 12697-17)

Asphalt sample	Initial Mass (g)	Final mass (g)	% Loss
SMA 11	1,250	1,232	1.40
PA 11	1,115	1,012	9.24
OSMA 11	1,200	1,152	4.00
SMA 8	1,238	1,220	1.50
PA 16	1,101	818	25.70

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The Cantabro test has proven to be a valuable tool for evaluating mass loss in porous asphalt (PA) mixtures with minor formulation changes, such as variations in binder type, use of fibres, or the incorporation of polymer additives. However, its applicability is limited when comparing asphalt mixtures of markedly different typologies, as is the case in this study. The test does not reflect actual wear behaviour under real traffic conditions, and the results cannot be reliably used to assess or compare the in-service durability of dense versus open-graded asphalt surfaces.

As expected, the porous mixtures in this study exhibited higher mass loss values, which are consistent with their structural characteristics and fall within typical ranges reported in the literature. Conversely, the dense-graded solutions showed relatively lower values, but this contrast is more a reflection of their intrinsic design differences than of their true resistance to traffic-induced wear.

Therefore, while the Cantabro test results are reported for completeness and internal comparison, they should not be interpreted as a direct indicator of wear performance in real-world applications. Nevertheless, within the scope of this test, it is noteworthy that the OSMA-11 mixture demonstrated an optimal balance, combining structural cohesion with moderate macrotexture, and resulting in one of the lowest particle loss values among the open-graded alternatives. This performance reinforces its potential as a promising candidate for reducing non-exhaust particle emissions while maintaining mechanical integrity.

6.6. Mechanical Evaluation

The mechanical performance of asphalt mixtures is a critical factor in assessing their suitability for long-term service under traffic loads. In the context of the LIFE NEEVE project, as stated in Chapter 5.3, evaluating the stiffness modulus, resistance to permanent deformation and fatigue behaviour will allow for a better understanding of how each pavement configuration contributes not only to structural durability but also to the generation of NEE.

In this context, following the recommendations of both Spanish and European regulations, standardised mechanical test (as described in Section 5.4) were conducted for all asphalt test samples (except where not technically feasible). The results are shown in Table 17:

Table 17. Asphalt mechanical evaluation

Mechanical Test	Standard Test (UNE-EN)	SMA 11	PA 11	OSMA 11	SMA 8	PA 16
Stiffness (MPa)	12697-26	2,383	1,976	2,952	2,513	2,741
Wheel Tracking, WTS (mm/10 ³)	12697-22	0.070	0.064	0.031	0.070	0.053
Fatigue resistance, ϵ ($\mu\text{m}/\text{m}$)	12697-24	191.05	-	124.64	147.87	-



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These results show that OSMA 11 consistently outperforms the other test samples across the mechanical test. It exhibits the highest stiffness modulus, indicating excellent resistance to elastic deformation under load. Additionally, in terms of rutting resistance, it achieves a remarkably low WTS value (significantly lower than the other mixtures) highlighting its ability to maintain surface integrity under traffic-induced shear stress.

The fatigue test further reinforces the OSMA 11 mechanical behaviour, as the strain value obtained demonstrates good endurance against repeated flexural loading. It is important to note that, due to their highly porous and open-graded structure, fatigue test has not been evaluated for the PA 11 and PA 16 mixtures.

Overall, these results confirm that OSMA 11 provides the most favourable balance between rigidity, resistance to deformation and fatigue performance, positioning it as the most mechanically robust solution among the tested alternatives. This robust mechanical profile complements its advantageous texture and drainage behaviour, making OSMA 11 a strong candidate for durable, low-emission pavement applications.



7. Future Outlook

The work conducted in the LIFE NEEVE project so far has laid a robust foundation for understanding the influence of asphalt pavement design on NEE. However, several critical lines of research remain open to further validate and enhance the findings obtained in this initial phase. In this regard, two main directions will guide future laboratory activities.

First, it will be essential to confirm the emission behaviour of the developed mixtures with respect to the generation of NEE. This includes both additional laboratory-scale assessments and the development of representative prototypes that allow the simulation of tyre-pavement interaction under more realistic conditions (which is currently undergoing). These tests will seek to confirm the replicability and stability of low-emission characteristics under variable mechanical and environmental stressors, as well as their long-term behaviour. VTI has access to most of the methods mentioned in Section 5.2 and can do such supplementary tests.

Although the Cantabro test did not work well for our comparison of asphalt samples, its usefulness is in comparing the effect of small design changes in PA and for this reason it may be used later in NEEVE, in which case the experience gained here may be useful.

Second, further research will focus on exploring the role of specific additives and alternative materials (steel slag particles) that may improve the polishing and abrasion resistance of the asphalt mixtures considered. The identification and optimisation of such materials will require a multidisciplinary approach, combining mechanical testing, particle characterisation, and environmental risk assessment.

Although not included in the experiments here, it is suggested in the theoretical sections that an SMA or PA with steel slag replacing the natural aggregate has a potential to become a novel pavement with good NEE properties to be tested later in NEEVE.

In parallel to these laboratory efforts, the ultimate performance of the proposed asphalt mixtures will need to be validated under real-world traffic and climatic conditions. Field implementation of selected pavement types is planned during the subsequent phases of the project, as part of LIFE NEEVE pilot demonstrations. These real-scale deployments will enable the monitoring of NEE in operational environments, assess the durability of the low-emission surfaces, and provide critical data to support policy recommendations and scaling strategies.

Together, these activities will ensure that the innovative pavement designs developed within LIFE NEEVE can evolve from experimental configurations to practical, replicable solutions for sustainable road infrastructure.

8. Conclusions

This deliverable has examined the potential influence of asphalt pavement design in the generation and mitigation of NEE, with a specific focus on the mechanical interaction between tyres and road materials. Through an extensive combination of literature review, laboratory formulation, and standardised testing protocols, it has been possible to characterise the physical, mechanical and textural behaviour of five asphalt mixtures (ranging from a conventional dense SMA to PA and hybrid configurations).

The methodology has allowed for the systematic comparison of mixtures in terms of abrasion resistance, particle loss, texture development and drainage capacity, all of which are directly or indirectly linked to the potential emission of particulate matter. Based on this approach, a number of findings have emerged that are particularly relevant for the design of low-NEE road surfaces, which are summarised as follows:

- The state-of-the-Art section of the Deliverable gave a detailed insight into the performance of various pavement materials with their potential influence on particle emissions.
- Among the tested pavement configurations, the OSMA 11 solution emerged as a particularly promising solution. It combines the mechanical robustness of SMA-type mixtures with enhanced macrotexture and void structure similar to porous asphalt, without fully compromising durability, showing that:
 - Improved resistance to particle loss (Cantabro Test).
 - Balanced macrotexture that favours friction and limits aggregate detachment.
 - Potential benefits in resuspension mitigation due to its open structure.
- All tested mixtures met the consortium expectations in terms of stiffness, rutting resistance, and friction. However, OSMA 11 outperformed other variants in the combined assessment of surface characteristics relevant to NEE, making it a strong candidate for real-world validation.
- The laboratory campaign has suggested that certain surface designs can support both traffic safety requirements and environmental objectives, by minimising aggregate loss, providing good drainage and thus indirectly reducing tyre .
- The experimental methodology defined in this deliverable establishes a replicable testing protocol that can be applied in future material development stages, pilot deployments, and policy support actions.
- However, other wear tests must supplement or replace Cantabro in testing asphalt samples with results that can represent real road performance under traffic.
- Although not included in the experiments here, it is suggested in the theoretical sections that an SMA or PA with steel slag replacing the natural aggregate has a potential to become a novel pavement with good NEE properties to be tested later in NEEVE.



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In summary, the results presented in Deliverable D2.4 reinforce the strategic relevance of pavement design in the context of sustainable mobility and urban air quality. The OSMA 11 mixture, in particular, offers a technically sound and environmentally beneficial solution that merits full-scale implementation and monitoring in the pilot phases of the LIFE NEEVE project.

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