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Road Pavement, Road Pollution, and Sustainability under Climate Change Increased Temperature

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Abstract: This paper presents a multidisciplinary approach to understand the impacts of temperature increase on the retention of particulate pollutants, such as heavy metals and microplastics, by the road pavement material. A soil with a particle size distribution similar to road dust was selected. A Wheel Tracking device was used to assess the permanent deformation behavior of prismatic specimens and the retention of the dust, at controlled temperatures of 40 °C and 60 °C, likely to occur on pavement in the future. The soil representing road pollutants was placed at the top of the slabs prior to the Wheel Tracking Test (WTT), based on the European Standard EN 12697-22:2020. After the WTT, two common methods were used, in order to evaluate the soil retention (pollution accumulation) on road pavement. The results confirm that the viscoelastic behavior of bituminous mixtures under increased temperatures can contribute to particle retention at the pavement. Future studies are needed to understand the phenomena, the retention characteristics by different bituminous mixtures, and the efficiency of pollutants capture. The work opens the opportunity to develop innovative road pavement bituminous mixtures that can reduce the discharge of road particulate pollutants, and have increased resilience and sustainability in extreme weather conditions.

Keywords: climate change; bituminous mixtures; heat effects; new methodologies; road pavement materials; road runoff pollution; sustainable development

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1. Introduction

1.1. Climate Change Impacts on Road Pavement and Road Runoff

Climate changes are foreseen as scenarios with higher temperatures and extreme rainfall (droughts and floods), as well as sea level rise. Such meteorological conditions will modify the behavior of road pavement materials, the water hydrological cycle conditions, and, consequently, road drainage processes and road runoff discharge. It is predicted that the climate will continue to change during the next century or even longer, depending on human activities alongside the lifecycle of Green House Gases (GHG) and the atmospheric systems that promote climate changes [1].

Several research studies evaluate direct and indirect impacts of extreme rainfall in road pavement, road runoff quantity, and quality and in water resources. The task is not easy due to the uncertainties associated with future scenarios (e.g., [2–9]). Changes in precipitation will change the pattern of diffuse pollution sources, including road runoff discharge, in the coming decades.

Road operators and administration bodies are interested in studies that evaluate the impacts of climate change on road pavement structures. They feel the urge for measures aimed at ensuring both road safety and accessibility in future changed climates. The World Road Association [10], based on questionnaire responses from countries included in the five main Köppen–Geiger Climate Groups, reports impacts that are raising concern. Among them are rainfall variation (both increase or reduction) that can alter moisture balances and influence pavement deterioration. Table 1 contains a summary of reported effects and impacts of climate changes, including temperature increase, on road pavement.

Table 1. Relevant effects of climate change extremes on road pavements.

Extreme Occurrences	Relevant Effects on Road Pavements
Temperature top range are increased	– Flexible pavements experience a higher occurrence of rutting – Bituminous pavements display signs of bleeding – Bituminous layers undergo accelerated aging – Higher demand for maintenance – Higher risk of occurrence of bushfires
Decreased temperatures and augmented freeze–thaw occurrences	– The bearing capacity decreases – Bituminous pavements may suffer from cracking, raveling, and the formation of potholes – The demand for pavement maintenance, including deicing, rises
Higher frequency of storms and higher rainfall intensity	– Water levels tend to rise – Road drainage systems may become inadequate, resulting in flooding – The bearing capacity is diminished – Cracking and permanent deformation may occur – Higher risk of slope failure – Risk of road closure and loss of efficiency in the transportation service
Increase in droughts	– Surface roughness increases – Subgrade moisture tend to decrease – Issues related to salinity arise

According to Table 1, rainfall changes can modify moisture balances and induce pavement deterioration (cf. Figure 1). In addition, temperature can affect the aging of bitumen and, consequently, the pavement behavior. In Australia, the latter was estimated to represent an increase in embrittlement of the surface chip seals of more than 90% of the rural sealed roads. Austroroads [11] considered that the life of bituminous surface treatments will be affected by ambient temperature; the increase in temperature will accelerate the rate of deterioration of seal binders and require earlier surface dressings/reseals, which will lead to higher maintenance costs. Mokoena et al. [12] show concern for the global warming and the need to appropriately decide on bituminous road materials for a reliable performance of asphalt roads in South Africa. Fletcher et al. [13] used observations, output from global climate models, and a statistical model to evaluate the extreme maximum pavement temperature in 17 major Canadian cities, concluding that for most of the cases there will be a projected increased temperature.

The most recent report from the Intergovernmental Panel on Climate Change [14] corroborates the concern, by estimating that the warming up for the period 2081–2100, compared to the years 1850–1900, may vary from 1.4 °C up to 4.4 °C, in the very high GHG emissions scenario.

Li et al. [15] used the MAGICC/SCENGEN tool to simulate pavement performance deterioration over time, for sites in the USA with various climate change levels and pavement structures. Although they established that the modelling tool "was robust and effective", they acknowledged the importance of gathering experimental results. The HDM-III road deterioration model was applied by Chai et al. [16] to model the effects of climate change on flexible pavement deterioration in Queensland, Australia. The study concluded that the maintenance cost is expected to increase by nearly 30% under future climate change conditions. A recent study by Mulholland and Feyen [17] estimated the increase in operation and maintenance costs (O&M) of railway and road infrastructures across the 27 Member States of the EU and the United Kingdom, based on climate projections under RCP4.5 and RCP8.5. The authors concluded that under a 4 °C global warming level, increased levels of extreme heat would cause annual transport O&M costs to rise by €4.8 billion, corresponding to an overall 6.9% rise compared to current values. Some studies dedicated to the impacts of climate change regarding pavement maintenance are mainly focusing on pavement materials and maintenance costs, and the conclusions are based on modeling tools [18,19].

Figure 1. Pavement deterioration, with alligator cracking, after very heavy rainfalls during the winter (Portugal).

On the other hand, when evaluating road runoff, specialists are concerned with the transport and discharge of increased water volumes and increased flow rates during runoff events caused by extreme precipitation (e.g., [20–24]). While precipitation is clearly a critical issue of concern, temperature, expected to change as well, is not addressed much; although, it has already been correlated with the presence and concentration of pollutants (e.g., [25]).

Bieliatynskyi et al. [26] note that asphalt concrete road pavement is sensitive to ambient temperature variations which, together with mechanical impact from vehicle load leads to several damages and material deformations. The thermodynamic behavior of road pavement, as well as the reliability and durability of different mixtures, are of great importance and a concern for research and practice [27,28].

Flexible pavements, under current climate conditions, can reach temperatures between 40 °C and 50 °C in Southern Europe [29]. Therefore, under future climate conditions higher pavement temperatures are expected. It has been pointed out (e.g., [30]) that road pavement softening at elevated ambient temperature may be likely to aggregate particles accumulated at the surface, therefore, acting as a sink of pollutants and contributing to pollution retention and environmental protection.

1.2. The Road Pavement as a Sink and Source of Road Runoff Pollutants

Markiewicz et al. [31] listed sources of organic pollutants in road runoff, namely tire wear, brake lining, integrated vehicle components, car care products, fuels, oils and lubricants, road construction materials, concrete, and road paint. The main sources of emitted Polycyclic Aromatic Hydrocarbons (PAH) were vehicle exhaust gases, followed by tire wear, motor lubricant oils, road surface wear, and brake linings. Contributions from surrounding land use, such as agriculture, industrial, or urban areas, are also acknowledged (e.g., [32]). Solids or dust found in road pavement are originated from distinct sources and materials: pavement wear; construction sites or rehabilitation works; atmospheric fallout; anthropogenic wastes; and vehicles components deterioration—with tire wear being a relevant source [21,33,34].

Road dust is considered to be a very important source of particles in the atmosphere, and its characteristics are studied worldwide. The presence of heavy metals in road dust are related to both human health and ecological risks, due to their persistency in the environment, and they are, for these reasons, the focus of several studies [35].

Road runoff washes off and transports the pollutants accumulated at the road surface. The composition and the concentration of pollutants in stormwater depend on the rainfall pattern, road pavement material and construction, road slope, vehicle characteristics, wheel configuration, ambient conditions, and environmental aspects, among other variables (e.g., [36,37]). Therefore, the presence of particles at the road surface and of associated pollutants must be evaluated, since they are transferred into the environment and biota [34,38–42]. Total suspended solids (TSS) and turbidity are proposed as indicators of highway stormwater quality, for being positively correlated with the presence of pollutants, such as the heavy metals Cu, Pb, Zn, Cr, and Ni [41,43]. Baum et al. [43] proposed that the particular fraction of the TSS < 63 μm could be a surrogate parameter for metal pollution presence in urban stormwater.

Ahmad et al. [38] studied the road runoff dust and particle pollution from road dust in a huge city in Pakistan. The authors concluded that metals such as Cu, Cd, and Mn are attached to road dust and particles, and are likely to pose risks for human health and ecosystems, due to their toxicity and persistency. Cu, Pb, and Zn are commonly found in highway runoff [21,34,36,41,43–45] and are mostly responsible for the overall toxicity of road sediment samples [34].

Pollutants accumulated at the road pavement surface are transported to the surrounding soil and water bodies by precipitation (e.g., [46]); the assessment of impacts depends on a huge number of variables. It has been demonstrated that the discharge of even small concentrations of road runoff pollutants can lead to impacts in confined water bodies (e.g., [47]). It is not just the total concentration that must be evaluated; the fraction of pollutants present in dissolved or particulate form is relevant for impact evaluation and the design of treatment systems [32,48,49]. Several countries have already characterized national road runoff constitution and know which are the most relevant pollutants. It was demonstrated that national, regional, and local site-specific variables control such processes. Crabtree et al. [25], for the purpose of characterizing highway runoff, defined four climate regions in the UK, on the basis of annual average rainfall and annual average winter temperature. The study showed a trend, according to climate, for PAH and dissolved copper (Cu) concentrations. Roads located in different climatic regions, even within a small country as is the case in Portugal, showed different patterns for road runoff quantity and quality (e.g., [44]).

Several strategies are used to deal with road runoff pollution, such as the control at source (reduction of pollutants' emissions) or the construction of treatment systems that receive the runoff from the road and discharge it to the environment, with a reduced concentration of pollutants. The removal of solids and particulate pollutants are among the operations targeted in these treatment systems. Yun et al. [50] indicate that around 80% of highway particles are <0.05 mm. Kayhanian et al. [51] report the difference between particles found at the road pavement surface and the ones that are likely to be washed out by rainfall events (smaller fractions). At least 55% of particles found at a highway and a parking lot surfaces were <0.6 mm. Rommel et al. (2021) [49] studied filter media removal of particles from road runoff and found that, according to several authors, they are predominantly present in the fine fraction (<63 μm).

Drygiannaki et al. [45] studied the content of heavy metals (Cd, As, Cu, Cd, Hg, Ni, Pb, and Zn) in stormwater sediments, and assessed the correlation of metals to finer particle fractions. For instance, Cd was strongly associated with particles sized > 63 μm and Cu to lower than 0.45 μm sizes. Kontchou et al. [34] and Baum et al. [43] agree that the adsorption of metals to road particles < 63 μm is most relevant, and that road sediment must be studied in order to prevent impacts in receiving waters and toxicity in the biota. Mahjoub et al. [52] studied tire and bitumen particles in several size ranges, from 37 up to 5000 μm. The research showed that most of the tire and bitumen particles were from the size range from 37 to 300 μm, and the tire particles were predominantly present in smaller sizes. Lange et al. [53] present similar results for rubber, bitumen, and other microplastic particles in highway runoff—the higher concentrations detected were associated with particles size fractions of 100 μm to 300 μm.

The adaptation of roads to climate change should be used to explore the performance of pavement materials and mix design innovation, as well as to combine it with pollution control strategies developing integrated solutions and responding to the challenges of sustainability. Research focused on the evaluation of the effects of temperature on bituminous mixture viscoelastic properties and its likeliness to affect particle retention at the road surface can contribute to new approaches for adaptation to climate change and for pavement sustainability.

2. Objectives

This study objective is to evaluate a novel hypothesis, namely if the impact of temperature increase on the viscoelastic behavior of bituminous mixtures can contribute to dust and particle bond pollutant retention within the pavement material. The work also aims at testing and proposing new experimental approaches designed to evaluate the formulated premise.

The experimental procedure established was based on a combined knowledge of pavement material characteristics and behavior, road drainage, and road particulate pollution characteristics. The laboratory methodology includes the use of apparatus designed to evaluate the permanent deformation behavior of bituminous mixtures, on the simulation of particulate pollution accumulation, and of particle retention by a bituminous mixture under increased temperature.

3. Materials and Methods

3.1. Soil Selection

A soil with geometrical and physical characteristics comparable to road pollution particles was chosen for the purposes of the test. Figure 2 shows the soil size fraction characterization. Most of the soil particles (89%) are <0.074 mm diameter. This description is within the ranges of particle dust present in road pavements found in the literature [49,51], as well as particulate pollutant fractions [34,41,43,45]. The characteristics of particles found at each road are dependent on site-specific conditions, including surrounding geology, soil type, and land use, as well as on the road pavement materials and vehicle characteristics. This was one of the reasons why sediments from a specific road were not used, as other authors had (e.g., [54]), ensuring that the results would not be biased by specific physical characteristics of particles from a given road location.

3.2. Bituminous Pavement Specimens Preparation and Testing Equipment

Four bituminous mixture slabs of 305 mm × 305 mm × 50 mm thickness were selected for the study. Both sides of each slab were used. The tests were performed at LNEC's Transportation Department. The slabs (specimens) were produced in the laboratory with bituminous mixtures used in flexible pavements in Portugal, with a 35/50 nominal penetration bitumen. This material is typical for pavement-wearing courses nowadays, all over Southern Europe. These specimens were washed with tap water, identified, weighed, and dried in a proper laboratory dry room with a constant temperature of 30 °C. The soil was also kept in the same dry room, to prevent changes in density and water retention.

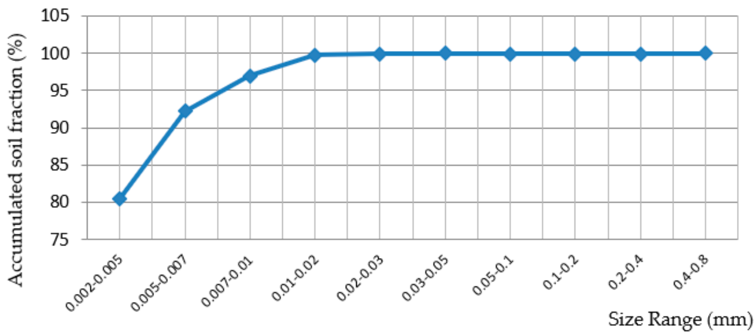


Figure 2. Characterization of the soil mass used in the tests in accordance with the accumulated fraction for different size ranges.

The testing apparatus used was a Wheel Tracking Machine (Figure 3a). This equipment is used for the evaluation of permanent deformation behavior of bituminous prismatic specimens (two at each time) under controlled temperature, producing results of the wheel-tracking slope, in mm per 1×10^3 load cycles, and comprises the application of controlled compression. The European Standard EN 12697-22:2020 [55] procedures were followed for this test. The compression is made by a wheel with 200 mm diameter and 50 mm width of solid rubber, on each specimen, simulating loaded vehicle wheel pressure on road pavement surfaces.

3.3. Procedures to Evaluate Particles Retention at High Temperature

The Wheel Tracking Test (WTT) required that the specimens were placed in the Wheel Tracking Machine 6 h before the test start, as specified by the standard. The temperature targeted for the test was programmed. The first 4 h are required for the testing equipment to reach the set temperature, and 2 additional hours are needed for all parts of the slabs to reach the target temperature and to stabilize. This latter stage is called temperature conditioning. After this conditioning, the wheel is rolling and compressing the slab during a period of 6 h, which corresponds to 1×10^3 load cycles, or until a rut depth of 20 mm is reached. During testing, the temperature is constant with variations within ±3 °C and the slab surface shape is measured and recorded by laser, at least at three cross-sections.

After test completion and cooling down to room temperature, the slabs were removed from the equipment.

For the purposes of studying road pollutants and the control of road runoff pollution discharges, a particle-based approach is frequently used to represent the physical processes of pollutant detachment, deposition, build up, and wash-off [22,41]. Furthermore, the simulation of rainfall and wash-off of pollutants from road pavements, in laboratory and field conditions, as well and road dust collection (sweeping, use of vacuum cleaners, wet vacuuming, etc.), are procedures used to study road dust, as well as pollution accumulation and removal from pavements (e.g., [36,40,43].)

Two procedures were designed to assess the retention of particles by the specimens, using the WTT device already described. One was based on spreading an amount of soil all over the slab and, after the WTT, removal of the excess of soil (not retained by the specimen) using water. The second procedure, based on dry removal of the excess of soil, focused only on the strip of the slab that would be compressed during the WTT. The two procedures are described in detail below, and are illustrated in Figure 4.

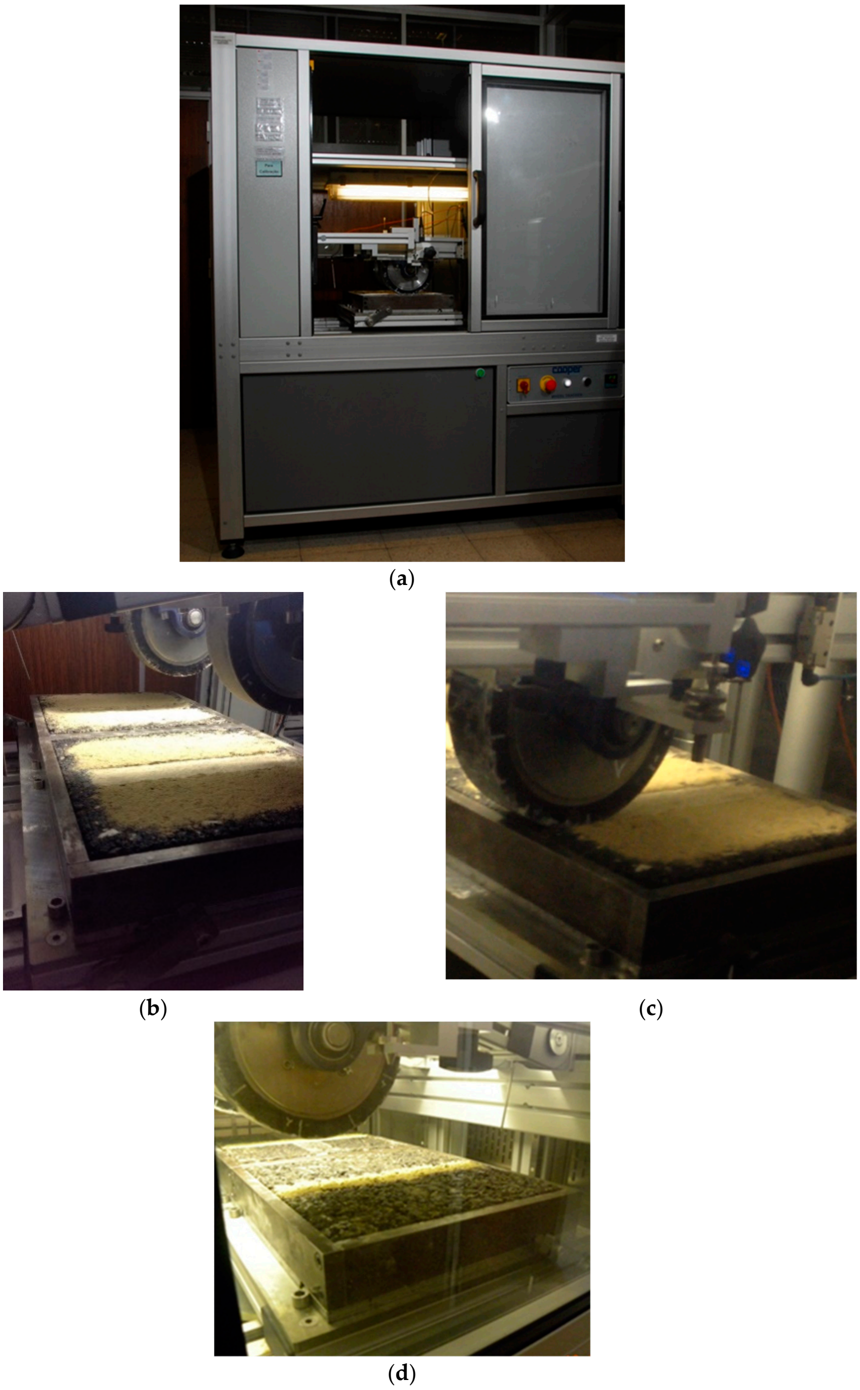


Figure 3. Wheel Tracking equipment (**a**). Test with 30 g of soil over the specimen (**b**,**c**). Test with 5 g of soil over a 5 cm strip (**d**).

i. **Wet removal of excess soil**

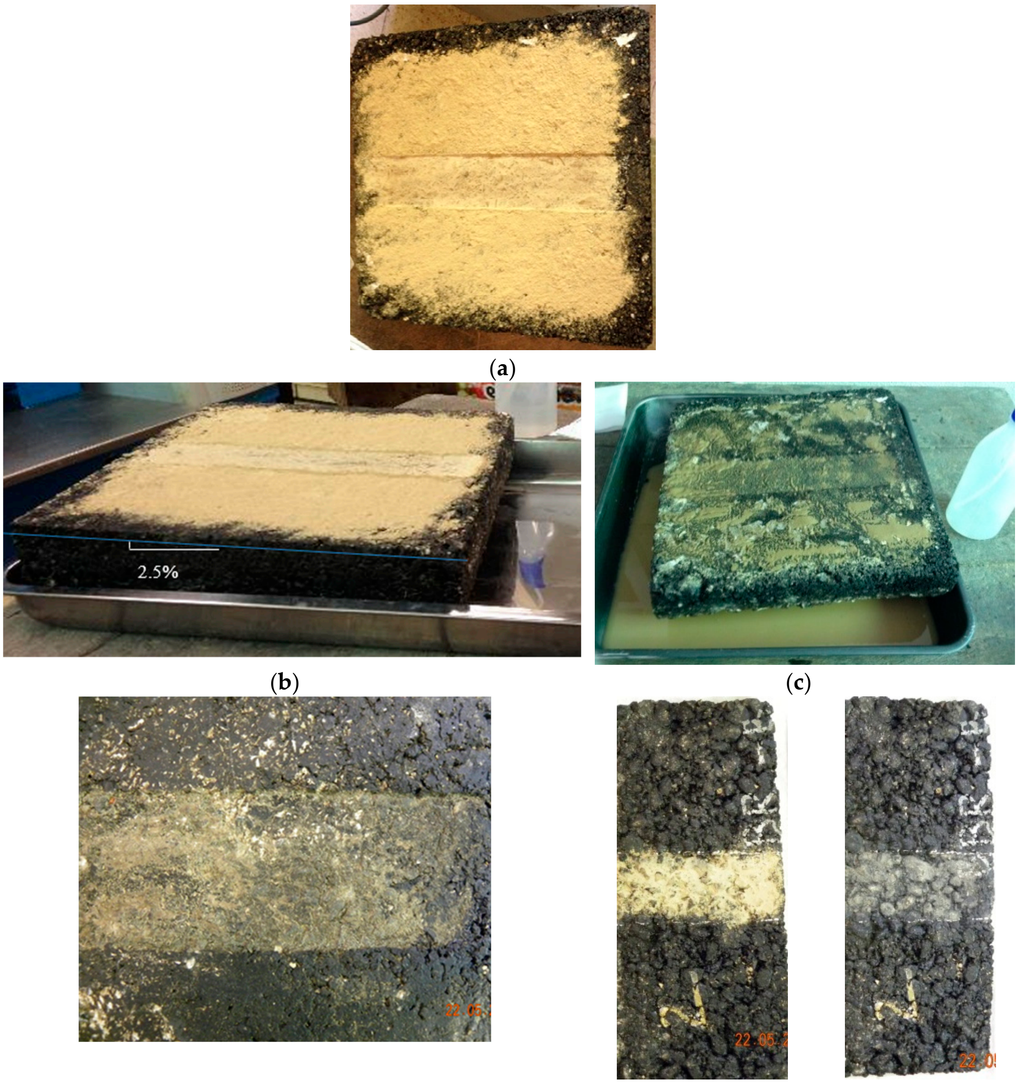
A total of 30 g of soil was weighed and manually spread, as homogenously as possible, on the entire surface of the specimen that would undergo the WTT, cf. Figure 3b,c. After the test conclusion and when room temperature was reached, each slab was placed inside an inox container of 35 × 50 cm, supported by a metallic basis with a slope of 2.5%, similar to common pavement cross-section slope. Then, the surface was washed out with 500 mL of deionized water, during 5 min, trying to remove as much of the surface soil as possible. The specimen was taken to the dry room for some days, until it reached constant weight. During the different stages, each specimen was weighted and several pictures were taken.

The inox container was taken to an oven at constant 100 °C until the soil was dry, and at that time the dry soil was weighted.

ii. **Dry removal of excess soil**

A total of 5 g of soil was weighed and manually spread only over the 5 cm strip of the specimen that would be directly under the rubber wheel during the WTT, cf. Figure 3d. After the test conclusion and when room temperature was reached, the slab undertook a process of soil removal: (i) Vacuum aspiration (900 W power device); (ii) Brushing; (iii) Vacuum aspiration, repeated twice. The vacuum equipment was weighed before and after this particle removal process, allowing to estimate the removal of soil from the specimen.

In order to have an indicator of the sensitivity to temperature, tests were performed at 40 °C and 60 °C. The latter aimed to simulate the wearing course behavior under the climate change scenarios. During the different testing stages, the slab specimens were carefully observed, and pictures were taken (Figure 4).



(**a**)

(**b**) (**c**)

(**d**) (**e**) (**f**)

Figure 4. Illustration of steps of the two procedures for the removal of soil after the WTT. *Procedure (i) Wet removal of excess soil:* (**a**) Slab with 30 g of soil all over the surface after Wheel Tracking Test at 60 °C. (**b**,**c**) Slab being washed with deionized water. (**d**) Slab with soil particles retained after being washed and dried. *Procedure (ii) Dry removal of excess soil:* (**e**) Slab with 5 g of soil over the area of the wheel path, after WTT at 60 °C. (**f**) Slab with soil particles retained after being brushed and vacuum cleaned.

4. Results

The WTT test, performed according to the dedicated standard, considers the assessment of maximum rut depth, creep slope, and number of passes. However, taking into consideration the main purpose of the work, the target results focused on assessing the impacts of temperature increase on the pavement material structure and on the retention of particulate pollutants. Tables 2 and 3 present the results for the soil retention by the slabs, under the 40 °C and 60 °C WTT. Figure 5 compares the soil particle retention by the slabs, at 40 °C and 60 °C.

Table 2. Soil retention by the slabs after the wet removal procedures (use of 30 g soil).

Slab	T (°C)	Soil Mass (g)				% Soil Kept	Particles Retained (g/cm^2)
		Placed at the Surface	Collected	Kept within Slab	Average Soil Kept		
BBR1	40	30	26	4	4	13%	0.0043
BBR2	60	30	18	12	11.5	38%	0.012
FOSSA2	60	30	19	11			

Table 3. Soil retention by the slabs after the dry removal procedures (use of 5 g soil).

Slab	T (°C)	Soil Mass (g)				% Soil Kept	Particles Retained (g/cm^2)
		Placed at the Surface	Vacuumed	Kept within Slab	Average Soil Kept		
BBR2	40	5	3.4	1.6	1.6	32%	0.010
FOSSA2	40	5	3.4	1.6			
BBR2	60	5	3.2	1.8	2	40%	0.013
FOSSA2	60	5	2.8	2.2			

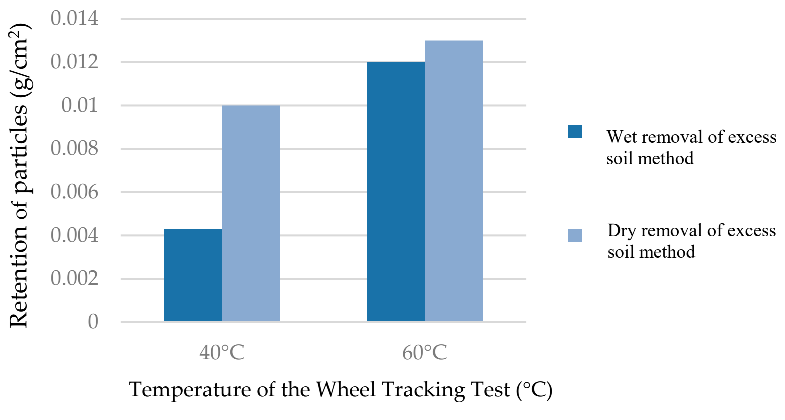


Figure 5. Comparison of soil particles retained within the slab after the two procedures (wet and dry removal).

The results for the wet removal procedure, presented in Table 2, include one test at 40 °C that was used as an indicator. The results show a soil retention by the slab of 13% at 40 °C and of 38% at 60 °C. It is understood that there is a different behavior at each temperature, corroborated by the Table 3 figures. The quantification was not an objective of the study, which is consistent with the limited number of samples, with the same asphalt mixture.

For the dry removal of exceeding soil (Table 3), the quantification of the amount of soil that remained embedded in the slabs should be merely indicative, due to the fact that some soil was lost during the brushing. The vacuum cleaner (itself with a weight of 1.848 kg) contained, respectively, 3.4 (at 40 °C) and 3.2 g or 2.8 g (at 60 °C) of soil at the end of the procedure. Therefore, from the total 5 g of soil, 1.6 g or 2 g remained embedded in the slabs' surfaces—which is visible in Figure 4f, for the 60 °C test.

Table 4 reports the weight variations that allowed the assessment of soil retention by the two slab specimens (BBR2 and FOSSA2) tested at 60 °C, according to the wet removal of exceeding soil procedure. FOSSA2 lost parts of bituminous material during the test procedure. Therefore, the measurement of 8 g of soil retained by this specimen after the WTT must be underestimated. The values of the washed soil are comparable (18 g and 19 g). Visual observation confirmed the presence of soil embedded in the surface of the specimen material—Figure 4d.

Table 4. Weight measurements during the different phases of the wet test at 60 °C.

Slab	Weight (kg)	Weight after 30 g of Soil (kg)	Weight after Test at 60 °C (kg)	Weight after Washing the Soil (kg)	Slab Weight after Dried (kg)	Weight of Soil in the Slab (kg)	Weight of Soil in the Inox Basin (kg)
BBR2	11.267	11.284	11.290	11.286	11.272	0.012	0.018
FOSSA2	10.683	10.97	10.697 *	10.695	10.675	0.08 *	0.019

* Loss of specimen material was observed during this step of the procedure.

The overall results (cf. Figure 5) show that there was retention of soil particles within the bitumen, and that the level of retention is higher at 60 °C compared to 40 °C.

5. Discussion

The presented approach showed itself to be feasible and a promising starting point to develop a methodology to be adopted in the future. The results confirmed that the viscoelastic behavior of bituminous mixtures due to bitumen softening under increased climate temperatures contributes to particles retention at the road surface and, consequently, may support road pollutant imprisonment. To what extent the phenomena occur and which is the strength of the retention, under different ambient temperatures and by distinct mixtures, must be assessed in future studies. It is understood that the results presented cannot be evaluated from a qualitative approach, given the limited samples used, but the confirmation of the hypothesis was possible, and the results are in line with outcomes from road runoff monitoring studies under distinct temperature climate regions. It is acknowledged that some dust particles may have adhered to the tires, during the WTT test. This process is similar to what takes place in real conditions, where not just vehicle tires but also the movement of vehicles passing and wind are processes that resuspend and may remove dust accumulated on the road pavement.

The test did not use road dust, as performed, e.g., by Bauer et al. [54], to avoid the possibility of biased results in the face of particles specific for a road location. Future studies should work with road particles from different locations, with distinct physicochemical characteristics and pollution content, to further understand particle behavior. Road dust can be easily obtained by collecting sediments at road runoff treatment facilities, or by vacuum cleaning sections of selected roads. Nanoparticles from road runoff sediment have distinct content of heavy metals—such as zinc, copper, lead, and cadmium—and microplastics, consequently having distinctive characteristics and causing differentiated impacts in the environment. Thus, the future research should also comprise the assessment of the pollutant content of the dust to be used.

The dry removal procedure used is more straight forward, and likely to allow the evaluation of total particles strongly embedded within the bitumen material. On the other hand, the wet removal method has the potential to be, in the future, fine-tuned to test the degradation of the pavement under cycles of heat/compression and rainfall, likely to take place under climate change scenarios, and can also contribute to understand the removal efficiency of rainfall events, in relation to its intensity and duration characteristics.

The proposed approach uses a standard procedure based on WTT with the application of controlled test conditions which allows a proper behavior comparison. The WTT standard test provides other results, such as the maximum rut depth, creep slope, and number of passes. Since the objective of the study was to validate the causal relation between heated pavement bituminous materials and dust retention at the road surface, the recommendation that was adopted concerned the use of controlled temperature and a rolling wheel. In fact, the procedure presented is an adaptation, considering the purposes of the experiment.

Future studies should consider adjustments and improvements to the procedures, to understand other variables not yet addressed. For instance, additional laboratory tests to characterize the bituminous mixtures should be considered, in order to evaluate asphalt performance under different climate change scenarios and with the incorporation of innovative materials that may enhance the retention of road pollutants [56].

Mokoena et al. [12] pointed out that pavement temperature relies on more than air temperature—it is determined based on various climatic and weather factors as well as on pavement material properties and the overall pavement structure. Future studies should be performed for distinct types of bitumen used in flexible pavements, as the retention potential can vary with the bitumen type. Baensch-Baltruschat et al. [33] recommend future studies to investigate environmental concentrations and the degradation of polymer compounds under environmental conditions. Among the mitigation measures to be implemented, according to the principle of precaution, there is the "successive optimization of road surfaces", in line with the approach of the work presented herein.

6. Conclusions

This study was designed based on multidisciplinary knowledge in the scope of road pavement and road pollution. The motivation was the current necessity for innovative approaches to deal with economic, social, and environmental sustainability.

The most recent report from the Intergovernmental Panel on Climate Change [14] supports the relevance of being prepared for temperature increases. Although the assessment of temperature impacts on road pavement behavior and resilience are the topic of theoretical, experimental, and modeling studies [27,28], there is not much research linking these objectives with road pollution control. In fact, the use of pavement materials to control non-point pollution from roads is not common. There is the example from Huang et al. [56], who studied the possibility of using a permeable reactive road asphalt pavement designed to capture volatile organic compounds produced by vehicles and, therefore, ensure some control of road pollution.

It is relevant to establish combined laboratory procedures to evaluate both pavement behavior at high temperatures, such as its rutting resistance or fatigue behavior, as well as the pollution retention effect. These new methodologies should aim to enable optimization of the final bituminous mixture design. The development of new types of bitumen, capable of ensuring adequate performance and with the capacity to incorporate particulate pollutants and present an improved behavior, would provide an answer to sustainability under climate change, pollution control, and the reduction of toxicity discharged by roads. Given the increased tendency to use cold or temperate bituminous mixtures in order to reduce the pollution during fabrication, transport, and laying of the asphalt, it is also important to study these types of materials and their aptitude to absorb/retain contamination.

This work opened opportunities to combine the reduction of pollutants discharged into the environment with new bituminous mixtures for improved road pavement resilience and sustainability. The future target is to expand and consolidate the work started, through laboratory and field research, facilitating the establishment of normalized tests and adaptation guidelines for road pavement materials, considering the accumulation of pollutants at the road surface, and consequently contributing to minimize economic, social, and environmental impacts.

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