recycling

Article

Skid Resistance Performance of Asphalt Mixtures Containing Recycled Pavement Materials under Simulated Weather Conditions

Maria Pomoni * and Christina Plati

Department of Transportation Planning and Engineering, School of Civil Engineering, National Technical University of Athens (NTUA), 5, Iroon Polytechniou, GR-15773 Athens, Greece; cplati@central.ntua.gr
* Correspondence: mpomoni@central.ntua.gr

Abstract: One of the challenges of using recycled materials in road structures is to maintain safe and durable pavements. A multitude of research has been conducted over the years on various recycled materials, with a focus on the structural performance of pavements. Another crucial, but almost overlooked, aspect is the pavement's ability to provide adequate skid resistance for road users under different climatic conditions. With this in mind, the present study aimed to investigate the skid resistance of asphalt mixtures containing two different types of recycled materials under laboratory-simulated weather conditions. Conventional hot-mix asphalt (HMA) and mixtures containing either reclaimed asphalt pavement (RAP) for aggregate replacement or crumb rubber (CR) as a bitumen additive were prepared and tested at different temperatures and different surface conditions (i.e., dry/wet) following a wetting protocol. Skid resistance was measured using a British Pendulum Tester (BPT). The results showed that the recycled mixtures performed similarly to conventional ones in terms of the skid resistance when the temperature was varied and under variable simulated surface conditions too. In some cases, they performed even better than conventional mixtures. Overall, a promising potential is demonstrated towards the use of the investigated recycled materials in asphalt surface courses.

Keywords: recycled materials; skid resistance; weather conditions; RAP; crumb rubber; British Pendulum Tester

check for updates

Citation: Pomoni, M.; Plati, C. Skid Resistance Performance of Asphalt Mixtures Containing Recycled Pavement Materials under Simulated Weather Conditions. *Recycling* **2022**, *7*, 47. https://doi.org/10.3390/recycling7040047

Academic Editors: José Neves and Ana Cristina Freire

Received: 7 June 2022
Accepted: 17 July 2022
Published: 19 July 2022

1. Introduction

Designing, building, and maintaining resilient infrastructure is a clear goal for most countries in the world. In the case of roads, it is crucial to meet the ever-increasing demands of traffic and freight transport while road authorities have to operate under specific and limited budgets, which should also be used to maintain durable pavements [1]. In Europe, durable pavements are referred to as "long-life pavements (LLPs)". LLP is a type of pavement in which there is no significant deterioration of the subgrade or base courses, provided that the surface is properly maintained [2]. In the USA, the related term "perpetual pavement" refers to an asphalt pavement designed to last more than 50 years without requiring major structural rehabilitation, except for periodic resurfacing [3]. In other words, maintenance planning for these pavements is mainly triggered by a deteriorating pavement surface. Considering these observations, it seems challenging for researchers to investigate alternative solutions for pavement maintenance that could act in favor of the sustainability of the road infrastructure in the long term.

In recent decades, attempts have been made to use recycled pavement materials for both the construction and maintenance/rehabilitation of pavements [4–7]. It is a widely held belief that recycled pavement materials help meet environmental requirements by limiting the need for new material resources, which is also consistent with budgetary constraints [8]. They also contribute towards the creation of a circular economy [9]. However, pavement engineers face many challenges when incorporating recycled materials into pavement construction or rehabilitation [4,10]. This means that pavement engineers today need to have a solid background knowledge of the properties and potential limitations of recycled materials in order to use them effectively for safe, resilient, and functional roads.

The best-known example of recycled material being incorporated into pavements is the reclaimed asphalt pavement (RAP), which is used extensively around the world to reduce the need for virgin aggregates. It is mainly obtained by milling during the rehabilitation of existing pavements and helps minimize waste production [11]. In general, it should be noted that most research studies related to RAP have focused mainly on the structural performance of roads rather than on issues related to functional road safety. The main challenge for road agencies is to assess whether the use of high RAP contents in conventional hot-mix asphalt (HMA) can negatively affect the long-term performance of asphalt structures and, consequently, the life-cycle costs [12]. High RAP contents (e.g., more than 25% according to [13,14]) might reduce the mixture's cracking resistance because of the aged binder's brittleness [6]. Other issues include RAP homogeneity, changes in the rheological properties of the binder of RAP and its stiffening due to oxidation, volatilization and segregation [15], problems with durability due to the high stiffness and low ductility of RAP, and problems with the interaction between virgin and recycled aggregates. Nevertheless, there is an agreement that RAP is an environmentally friendly solution that performs satisfactorily in terms of the rutting susceptibility and water sensitivity when used in asphalt mixtures, even at high percentages [16,17]. More information about the advantages and disadvantages of RAP can also be found elsewhere, e.g., [6].

Another recycled material that may not have been studied as thoroughly as RAP is the recycled rubber derived from scrap tires and processed in the form of crumb rubber (CR) [18]. It has been mentioned that CR can improve the compound performance, extend the pavement life with lower maintenance costs, and potentially contribute to noise reduction [19]. Although the recycling of tire rubber for use in road construction is now mature, there is a different trend in its use worldwide, which depends, among others, on the number of new cars, which affects the recycling rate of the available scrap tire rubber [20,21]. For instance, in China, the number of new passenger cars is expected to double from 2016 to 2024, thereby necessitating the recycling of the scrap tires of existing cars that are to be replaced [20]. However, reclaiming waste tires for use in new ones is very limited due to the demanding process of re-vulcanizing rubber [21]. Therefore, alternative tire recycling solutions are in demand. To meet this need, roadway engineering and pavement construction/reconstruction might be a sector benefiting from the increased availability of waste tires.

Most of the relevant research studies have focused on evaluating the mechanical performance of crumb-rubber-modified compounds. For example, reactivated asphalt rubber mixtures have been reported to perform better than unmodified mixtures in terms of the moisture susceptibility, fatigue cracking, and rutting resistance [19,22,23]. On the other hand, reported issues with the use of CR include the storage stability of the modified mixtures because of the heterogeneity between binder and rubber particles [24] or potential detachment of aggregates in the case of dry mixing of binder with CR with poor cohesion [25]. More information about the advantages and disadvantages of CR can also be found elsewhere, e.g., [21].

Despite the increased potential of RAP- or CR-modified mixtures for the construction of structurally sound roads, there appears to be limited experience regarding the surface performance that these recycled materials could provide when selected to rebuild the top layer of a pavement. To the best of the authors' knowledge, limited studies have investigated the surface performance of mixtures containing recycled materials [9,16]. These studies revealed a satisfactory surface frictional performance of high-RAP mixtures supplementary to other mechanical tests (i.e., fatigue resistance, permanent deformation, water sensitivity, etc.). Among the various aspects of pavement surface characteristics (i.e., roughness, texture, rutting), this study focuses on skid resistance because it has a major impact on road safety.

Specifically, the authors have already developed a laboratory procedure to evaluate the skid resistance performance of asphalt mixtures containing recycled materials by studying the polishing behavior of these materials under simulated traffic exposure [26]. Building on these results, the objective of the present study was to investigate the effects of weather changes on skid resistance. In other words, the goal was to extend the existing knowledge by evaluating the skid resistance of asphalt mixtures modified with either CR or RAP under simulated weather conditions in a controlled laboratory environment and to obtain a more complete understanding of their behavior.

For this purpose, samples of asphalt mixtures were prepared in the laboratory to meet the standards for surface course mixtures. A laboratory-scale experiment was then conducted to simulate temperature variations, rainfalls (through water additions), and the presence of contaminants on the surface of the prepared samples in the form of slabs (test specimens). Measurements of the skid resistance were made using the British Pendulum Tester (BPT), which is used worldwide in both laboratory and field testing [27]. The whole experimental process was organized and implemented at the premises of the Laboratory of Pavement Engineering at the National Technical University of Athens (NTUA).

The rest of the study is organized according to the following parts: (i) a brief background on the performance features of skid resistance together with the use of recycled materials, (ii) a detailed description of the experimental process (i.e., details of the materials, specimen fabrication, and skid resistance measurements), (iii) a presentation/discussion of the experimental results, (iv) discussion points/limitations of the followed process, and (v) conducing remarks and future prospects.

2. Skid Resistance vs. Recycled Materials in Road Pavements

The skid resistance of pavement surfaces has been shown to be a contributing factor to traffic accidents, as it is related to the skidding of vehicles and thus the safety of road users [26,28,29]. Considering that nations worldwide have made road safety one of their national priorities [30], it is clear that any intervention methods or use of non-conventional materials for road pavements must meet the requirements for road safety. Therefore, it is of utmost importance that the use of recycled materials for pavement surfaces should promote driver safety.

However, uncertainties in the performance of recycled materials and the multi-parametric nature of skid resistance increase the complexity faced by pavement engineers in the design and maintenance of surface courses. The main factors affecting skid resistance include the aggregate type, mix composition, on-site compaction, traffic volume, vehicle speed, etc. [29]. Moreover, it is well known that skid resistance does not remain constant even over a short period of time (throughout the year) because, in addition to the traffic effect, it depends on a variety of weather factors that change seasonally or intermittently (temperature, rainfall, and presence of contamination on the pavement surface, etc.) [31].

Therefore, the study of the skid resistance of recycled materials is an area that needs to be explored, as there are only a few relevant research studies [16,32–35] with quite controversial results. Based on limited material data, Wang et al. [32] reported the promising potential of the use of asphalt mixtures with a high percentage of RAP in terms of skid resistance. Among the various properties tested, including both mechanical and functional behaviors, Antunes et al. [16] found a better performance of RAP mixtures in terms of skid resistance, but an insignificant decreasing trend was observed when considering an aged RAP mixture. In the same context, Eskandarsefat et al. [33] demonstrated a slightly better performance of dense asphalt mixtures with CR compared to conventional mixtures. On the other hand, Putra et al. [35] demonstrated that the addition of RAP and CR reduced the skid resistance. Such contradictory results might be related to the properties of the individually tested materials or other experimental- and case-dependent factors. Nevertheless, the contradiction itself proves that the frictional performance of recycled mixtures remains an “open” issue that is subject to additional investigation.

It is considered that the best method for obtaining knowledge about the performance of materials is to conduct tests under real environmental and weather conditions in an accelerated pavement testing (APT) facility. However, this procedure is both cumbersome and costly and may discourage pavement engineers and highway agencies from systematically investigating these issues at this time. In contrast, it makes more sense to test and evaluate the performance of new recycled materials through controlled laboratory testing to simulate weather and traffic conditions that occur in the field and understand their effects. In this case, the "lessons learned" can serve as a precursor to strategic planning of appropriate field investigations and further verification or improvement of laboratory-scale results. In either case, an effective experimental design must take into account the prevailing aspects of skid resistance performance, as described below.

Numerous studies have addressed the changes in skid resistance due to traffic polishing, the seasonal variations (over the year), and the challenges in quantifying these changes [36–38]. Once the pavement is placed in service, an initial increase in the skid resistance can be expected as the asphalt bitumen film of the surface aggregates (masking effect) is removed by traffic flow, affecting the macro- and microtexture components [26,39]. When the aggregates are then exposed without being covered by asphalt bitumen, variations in skid resistance occur, mainly due to the traffic effect and seasonal and/or short-term weather variations [40].

In general, a typical pavement shows a different performance in terms of the skid resistance during wet and dry periods. The main hypothesis is that after prolonged dry periods with limited rainfall, the skid resistance is lower due to surface contaminants and debris (fine dust, clay, loose gravel, rubber, vehicle oil, etc.) deposited on the road. Their presence affects the contact area between the tire and the pavement through the mechanisms of adhesion and hysteresis [40]. Adhesion is related to the development of molecular bonds formed at the contact area between the tire and the aggregate surface under high pressure while hysteresis is related to the loss of energy of the rubber compound in its effort to capture the profile of the pavement texture. During the wet months (periods of heavy rainfall), contaminants are washed and cleaned from the road surface, resulting in better skid resistance levels [36,41].

Temperature is also a factor that affects the skid resistance of the road surface [42]. However, modern rubber compounds for tires are formulated to compensate for the effects of temperature on the friction between the road surface and the vehicle at normal driving speeds. Nevertheless, skid resistance is usually lower at high temperatures because the rubber becomes softer (due to its viscoelastic nature) and hysteresis is affected more (more energy loss) [43,44].

3. Experimental Process

The general framework of the laboratory-scale investigation is shown in Figure 1 and is explained in detail in the following subsections.

3.1. Specimen Fabrication

3.1.1. HMA-CR Mixtures

To investigate the effect of CR additives, the specimen types described below were fabricated:

(1) A semi open-graded HMA with no crumb rubber additives: S-0.
(2) A semi open-graded HMA with crumb rubber additives: S-CR.

The asphalt mixtures were designed to meet the standard specifications for a pavement surface course with a maximum aggregate size of 12.5 mm. The aggregate gradation is presented in Figure 2. This gradation conforms to the O-5 mix designation for surface course mixtures according to [45]. The same aggregate gradation was followed for the CR-mixture considering the absence of relevant standards. Regarding the aggregates, they were of limestone origin and were collected directly from a batch plant before being used for asphalt mix production.

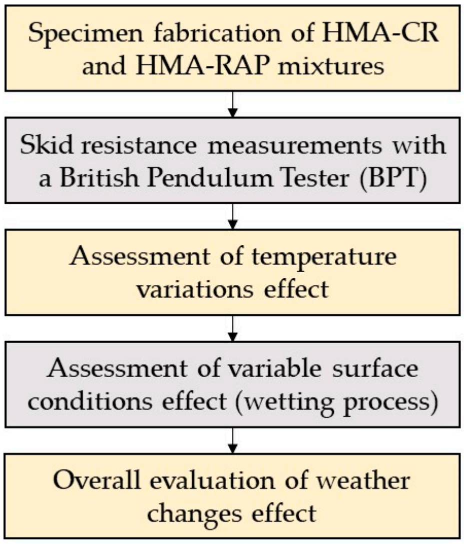

Figure 1. Study flowchart.

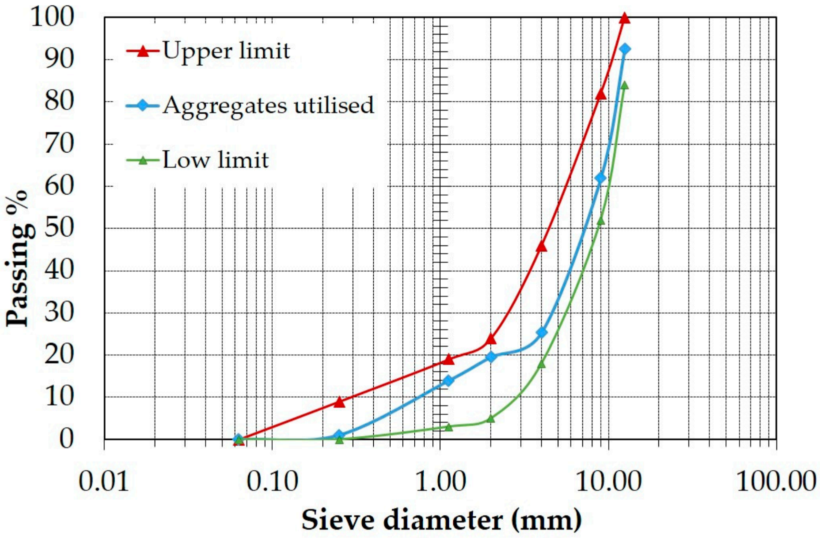

Figure 2. Aggregate gradation for the CR-modified mixture.

S-0 was defined as the reference mixture containing polymer-modified asphalt bitumen at the percentage of 5.4% by the mass of the mixture. The bitumen and HMA properties of S-0 are given in Table 1.

Table 1. Bitumen and HMA properties.

Bitumen Properties	Method	Values
Type	[46]	25/55–70
Penetration (PEN at 25 °C)	[47]	44
Softening point (°C)	[48]	75.8
Elastic recovery (%)	[49]	94.8
Density (kg/m^3)	[50]	1030
HMA Properties	**Method**	**Values**
Stability (kN)	[51]	11.3
Flow (mm)	[51]	4.4
Air voids (%)	[52]	10.9
Water sensitivity	[53]	0.82
Density (kg/m^3)	[54]	2245

For the fabrication of the S-CR mixture, CR additives were procured in the form of fine particles by a commercial entity that is responsible for proper processing of waste tires. Figure 3 illustrates the process to obtain CR from shredding waste tires through ambient grinding.

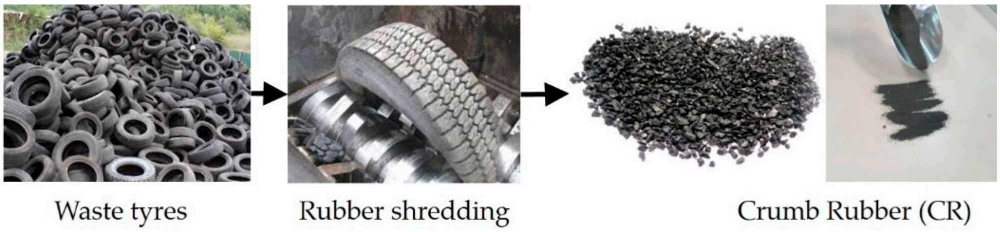

Figure 3. The utilized crumb rubber material.

It is worthwhile to mention that CR material in its physical state is a black fine viscous material with a bulk density of approximately 0.6 g/cm^3 and a flashpoint of greater than 300 °C. The material, on average, consists of 62% fine rubber, 22% soft bitumen, and 16% mineral stabilizer. In terms of its gradation, CR has individual particle sizes below 600 µm based on the information retrieved from the commercial supplier of the material. Furthermore, the majority of the individual rubber particles were concentrated in the range of 250–600 µm in size.

In terms of the mix composition, CR was added in the percentage of 10% by weight of asphalt bitumen to limit the original bitumen content. Similar approaches have been followed in relevant investigations, where, in the absence of relevant specifications/recommen- dations, the optimal dosages of crumb rubber have been reported to range from 5–20% [19,21,23]. In higher quantities, the binder becomes stiff [21]. Therefore, the selected dosage of 10% was considered as a mean approach. For the production of the modified mixture, CR was first added to the heated aggregates in a dry process at a mixing temperature of 180 °C and then, the modified asphalt bitumen was added.

Both S-0 and S-CR mixtures were maintained in an oven for 1 h at a temperature of 180 °C. After the 1-h heating, the S-0 and S-CR mixtures were placed in square molds (305 mm × 305 mm) for the rolling compaction process (Figure 4). The mass of the asphalt mixture required to fill the molds was calculated based on the asphalt mixture's maximum density and the desired (targeted) level of air voids. The roller compaction process took place through a multi-purpose, steel-segmented compactor and the method was based on [55]. For the current investigation, a static compaction force was applied to the surface of the materials within the mold. The achieved air void content of the S-0 specimen was around 11% and it was measured according to [52]. The air void content for the S-CR specimen was slightly lower (i.e., 10.5%).

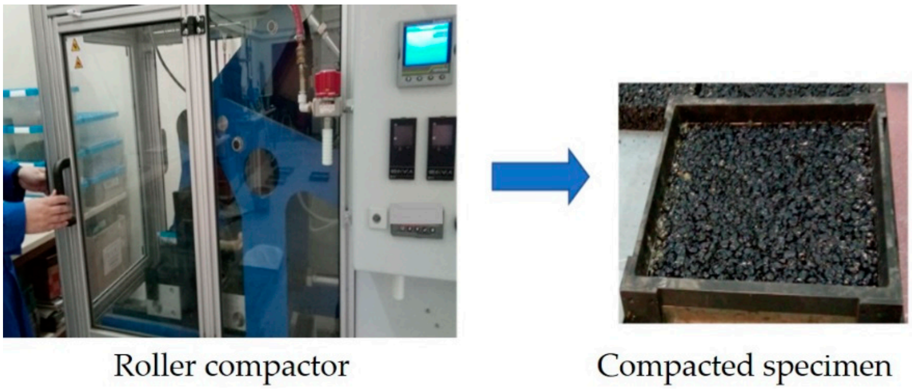

Figure 4. Roller compactor device (**left**) and a compacted specimen (**right**).

3.1.2. HMA-RAP Mixtures

For the current investigation, RAP material was collected on-site during pavement rehabilitation activities for research purposes (Figure 5). The related rehabilitated pavement was part of a heavy-duty interurban motorway in Greece that was around 5 years old. In particular, RAP material came from the surface course of the initial pavement structure.

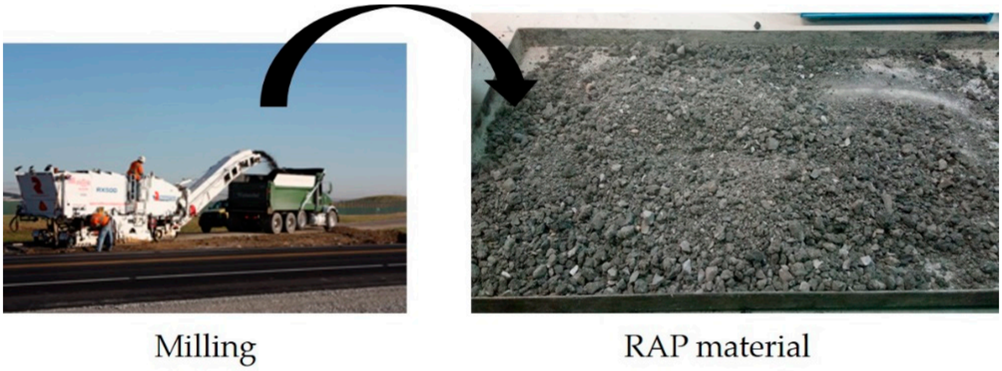

Figure 5. Reclaimed asphalt pavement (RAP) material.

The RAP material was based on the O-5 mix designation according to [45]. Steel slag was used in the mix design as aggregate type and a 25/55–70 asphalt bitumen was added. The mixture contained 5% asphalt bitumen by the mass of the mixture as determined from the bitumen extraction process [56]. The bitumen properties of the RAP were similar to those shown in Table 1.

RAP was blended in different proportions with fresh HMA mixture produced with the same characteristics of S-0. The specimens listed below were fabricated:

(3) A semi open-graded HMA with a 30% RAP content by the mass of the total aggregate mixture: S-R1.

(4) A semi open-graded HMA with a 15% RAP content by the mass of the total aggregate mixture considering only the fine RAP aggregates: S-R2.

Considering the absence of relevant standards for RAP contents, the previous compositions were selected based on the current state of practice and/or relevant recommendations made in the international literature mainly based on the optimal mechanical behavior of HMA-RAP mixtures [14,18]. The Federal Highway Administration (FHWA) has reported that there is a potential to use RAP up to 30% in the intermediate and surface layers without compromising the pavement performance compared to virgin pavements with no RAP [14].

Before the specimens' fabrication, the gradation of the RAP mixture (Figure 6) was carefully controlled to meet the same specifications as the S-0 gradation since RAP was intended to be used for surface courses with particular gradation limits, which are also shown in Figure 6. For the case of S-R2 though, only the fine RAP aggregates (less than 4 mm) were used in the percentage of 15% by the mass of the total aggregate mixture, with the aim to investigate potential differentiations in their performances.

HMA and RAP materials were heated and blended to produce homogeneous mixtures while a low amount of virgin asphalt bitumen (25/55–70) was added at the percentage of around 1% by the mass of the mixture. It is noted that the bitumen and virgin aggregates used for the HMA-RAP mixtures were identical to those used for the fabrication of the reference mixture (S-0).

Finally, mixtures were compacted using the roller compactor. The achieved air void contents were measured according to [52] and are shown in Table 2 together with the S-0 specimen.

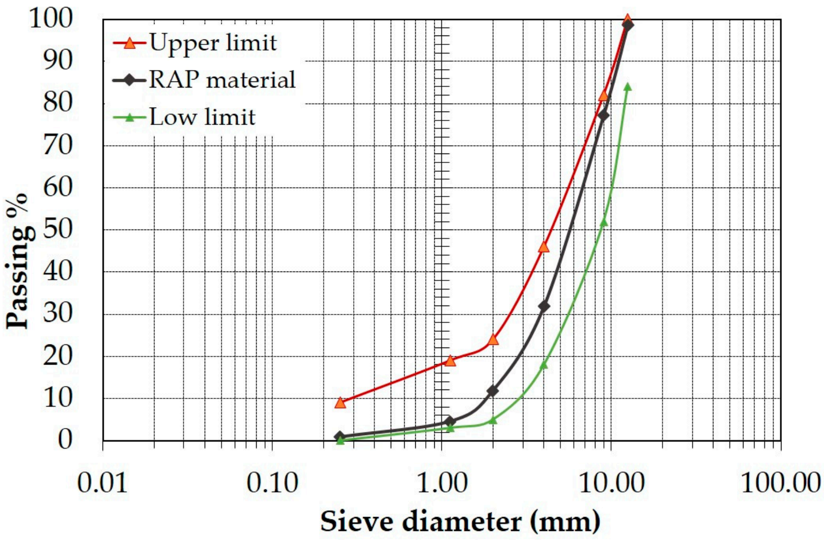

Figure 6. RAP gradation.

Table 2. The volumetric properties of all fabricated HMA-RAP specimens.

Specimen	Air Voids (%)
S-0	10.9
S-R1	7.7
S-R2	7.9

3.2. Skid Resistance Measurements

Skid resistance measurements were taken on the surface of the fabricated specimens with a BPT device (Figure 7). The BPT system is a portable friction device and is standardized according to [57]. The measurement output is given in terms of the British Pendulum Number (BPN), ranging in a scale from 0 to 150 BPN. A BPN value of 0 corresponds to a frictionless surface while a BPN value of 150 represents a rough surface with very high friction.

Figure 7. The utilized BPT device.

BPN measurements on each slab were performed in the center and at four points of a cyclic area, as shown in Figure 8, in two perpendicular directions. The final BPN value is the average of these five points. This approach was followed with the aim of minimizing the effect of roller compaction on the surface, which may cause small irregularities that could be detrimental for the BPN measurements.

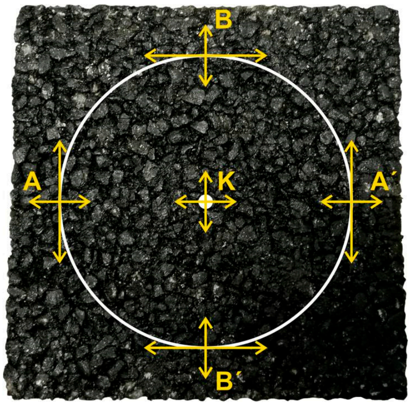

Figure 8. Slab points of the BPN measurements.

3.3. Simulation of Weather Conditions

3.3.1. Temperature Variations

In order to investigate the influence of temperature variations, each specimen was tested at a defined set of temperatures. Temperature variations were controlled based on proper preconditioning of both specimens (i.e., through a chamber) and the testing environment (i.e., through air-conditioning). In particular, the specimens were appropriately placed in a chamber before testing and were left for a minimum of 6 h to reach the desired temperature on their surfaces. In addition, the laboratory room was air-conditioned too in order to ensure the desired ambient temperature was similar to the testing temperature. The selected tested temperatures included the values of 10, 15, and 25 °C. Since the BPT slider directly contacts the specimen's surface, temperature was continuously measured on the specimen's surface to ensure that it had already reached the desired value before the beginning of the test (Figure 9).

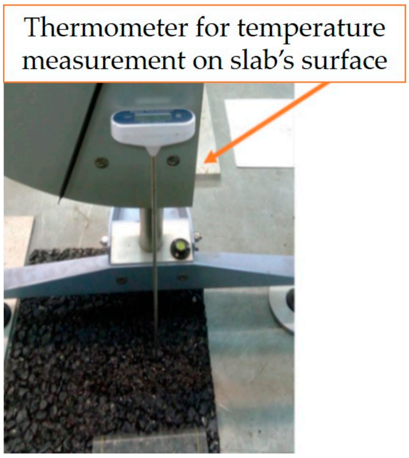

Figure 9. Temperature measurements on the specimen's surface.

It is noted that the testing took place during late autumn, so it was practically difficult to achieve preconditioning for the even higher temperatures that can be encountered during summer months. On the other hand, it would also be interesting to consider even lower temperatures and/or consider snow and icy conditions that are critical for slip resistance. However, such conditions are less likely to be encountered in the field in south Europe (i.e., the Mediterranean climate zone). Therefore, the selected temperatures corresponded to a typical and average temperature range that can be anticipated within an annual basis.

Given these issues, BPN measurements were taken as described previously and the average BPN value was considered as characteristic of each temperature.

3.3.2. Dry and Wet Contamination

The dry and wet phases were simulated in the laboratory environment by adopting a related wetting simulation protocol [58]. The aim of this protocol is to consider the weather variations reflected in the dry, wet, dry-dusty, and wet-dusty surfaces that a pavement is typically exposed to during its operation period. Therefore, the idea was to simulate a series of such on-site (real) conditions within a controlled laboratory environment. These conditions are illustrated in Figure 10, which presents both the considered on-site conditions and the corresponding conditions simulated in the laboratory. In order to limit the complexities of simultaneously considering the effect of variable weather conditions (i.e., both temperature changes and variable surface conditions), it was decided to adopt a constant temperature for the current stage of investigation. This temperature was set to 20 °C, which is the mean approach for a typical range of room temperatures (e.g., 15–25 °C) that have been also used for other similar investigations (e.g., [59]). In its generalized form, the wetting protocol that was followed for the laboratory simulation of the weather conditions on the fabricated specimens is shown in Figure 11 and described in detail thereafter.

The simulation process included the following:

- Phase (1)—“dry surface”: BPN was measured without the addition of water to the surface.
- Phase (2)—“water on clean surface”: Water was added (2–3 gr) and BPN was measured.
- Phase (3)—“dry and dusty surface”: In this phase, testing specimens were left for 2–3 days to become dry. Afterwards, a wet mixture of the finest aggregates consisting of sand and clay (20 g) with water (7 g) was spread on the testing surfaces, simulating the presence of contamination from loose debris on the pavement surface. Then, the specimens with the contamination were left to dry for a couple of days. Finally, the BPN was measured to assess the presence of the dry contamination.
- Phase (4)—“wet contamination”: The previously described mixture (water and finest aggregates) was added and BPN was measured immediately after.
- Phase (5)—“water addition up to cleaning”: A continuous rainfall event was simulated using this wetting process to wash off contamination by progressively rinsing water and measuring the BPN at each stage of the water showers. The addition of water stopped when there were no remarkable changes in the BPN levels (dBPN < ±2 BPN).

The process was repeated twice per specimen (after each process, the specimen was cleaned and dried effectively) and the maximum acceptable variance between the testing phases was considered to be equal to ±4 BPN. If the variance was greater than 4 BPN, the process was repeated with a third testing phase on the same specimen. Thereafter, the averaged results were used to interpret the experimental findings.

3.4. Remarks on the Experimental Process for HMA-RAP Specimens

This study is part of ongoing research on the skid resistance performance of asphalt mixtures with recycling materials, with an ultimate goal of developing a comprehensive laboratory-scale framework that could act as a precursor for future enhancement of the investigations. Considering that the aim of this study was to assess different weather conditions, which are, indeed, variable even locally, it was decided to slightly modify the testing procedure and circumstances for the HMA-RAP specimens.

On these grounds, the tested temperatures for the HMA-RAP specimens were changed to 10, 25, and 30 °C, including an even higher value (that of 30 °C). Further, phase (3) was performed for the S-0 and S-CR specimens, simulating a prolonged dry period (i.e., dry contaminated surface). This phase was omitted in HMA-RAP specimens in order to directly simulate the effect of rainfall on a wet contaminated surface (i.e., continuous water additions) and assess how contamination interferes with wet surfaces. As such, a different weather condition was approached and phase (4)—“wet contamination” was performed directly after phase (2) in the HMA-RAP specimens. These changes enabled the authors to gain insight into the distinct material behavior in order to propose a broader test protocol that will be able to perform a comparative assessment of different materials under identical weather conditions in the future.

Figure 10. Consideration of various weather conditions: (**a**) on-site status and (**b**) laboratory simulations.

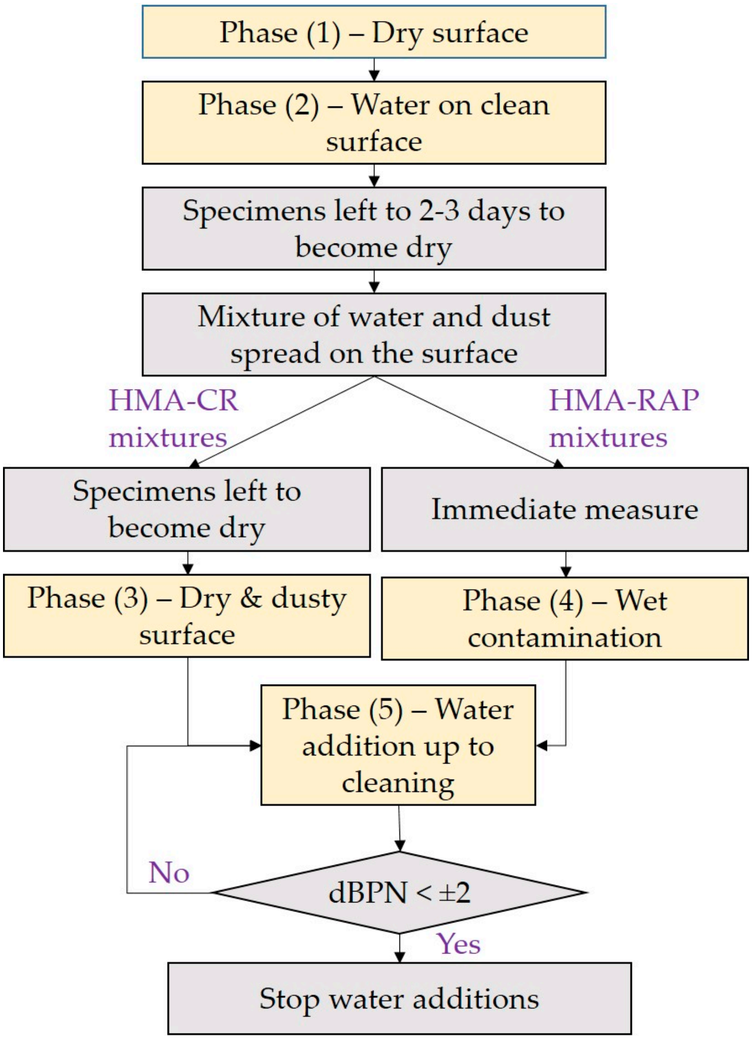

Figure 11. Methodology of the wetting process.

4. Results and Discussion

4.1. HMA-CR Mixtures

Figure 12 illustrates the effect of temperature changes on the asphalt mixture containing CR (i.e., S-CR) for each set of testing temperatures in comparison with the corresponding changes for the reference mixture (i.e., S-0). Additionally, the error bars with fixed mean error values were added. It is noted that the upper BPN threshold is 150; however, for a better visualization of the BPN differences, an upper limit of 100 BPN was set in Figure 12. This was followed for the next figures too, based on the presented values.

From the results, it appears that the increase in temperature from 10 to 15 °C caused a slight increase of around 5–7% in the BPN levels of both specimen surfaces (S-0 and S-CR). However, this finding is not in accordance with the state-of-the-art knowledge, according to which an increase in temperature decreases skid resistance levels. This finding may be attributed to the mixture components' interaction or other case factors related to the experiment and may require further investigation with additional samples. Nevertheless, the observed increase was tolerable. On the other hand, as the temperature increased from 15 to 25 °C, a clear decrease in the skid resistance in terms of BPN was noted. This is reasonable given that both asphalt and rubber compounds of the BPT slider tend to become softer due to their viscoelastic nature as temperature increases [44,60,61].

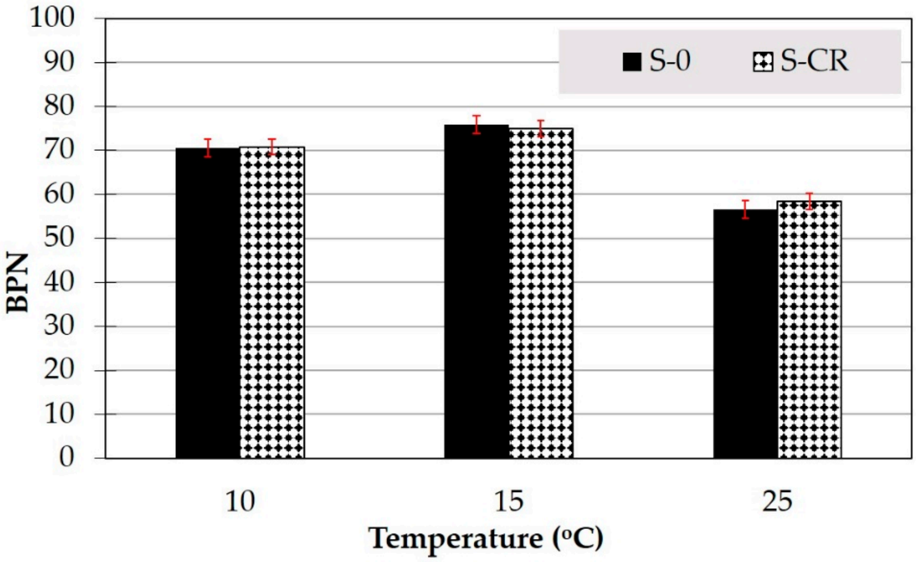

Figure 12. Temperature effect on the fabricated S-0 and S-CR specimens.

Overall, with respect to the CR impact, it seems that its addition did not produce clear evidence for an increase or decrease in the skid resistance at the tested temperatures, given the almost equal BPN levels for S-0 and S-CR at all tested temperatures. This remark is considered positive, as it seems that in this experimental process, the evolution trend of the skid resistance was similar irrespective of the materials used without any substantial differentiation at least for the factor of temperature changes. Consideration of additional temperatures could enable further elaboration of the material's effect against temperature changes.

Figures 13 and 14 show the BPN values for each stage of the simulated weather conditions on the specimens' surface based on the protocol that was previously described. The wetting process of phase (5)—"water addition up to cleaning" in Figure 14 took place after phase (3)—"dry and dusty surface", according to the added amount of water, which is shown in the horizontal axis. It is noted that in Figure 14, during each measurement stage of phase (5), the standard errors were rather low, and the error bars would be practically invisible. Hence, they were omitted.

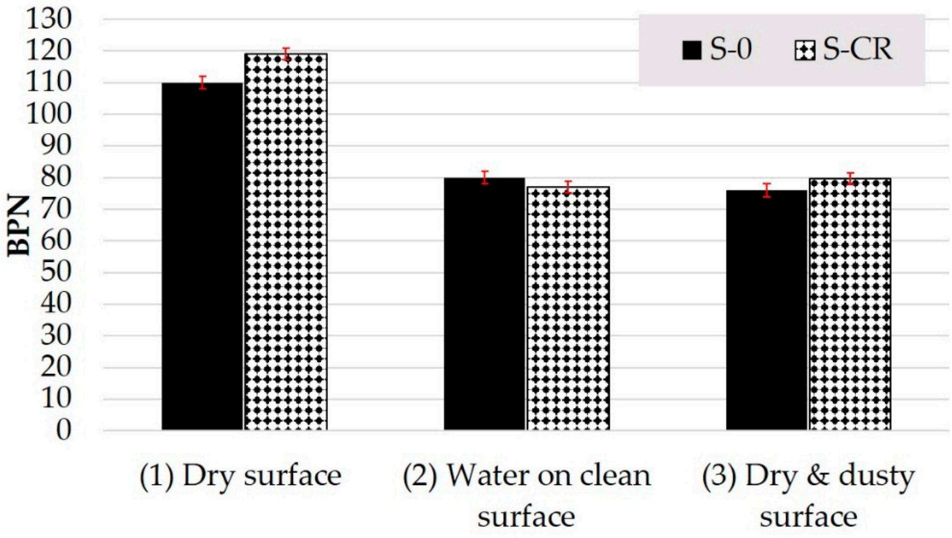

Figure 13. BPN levels during phases (1), (2), and (3) for the S-0 and S-CR specimens.

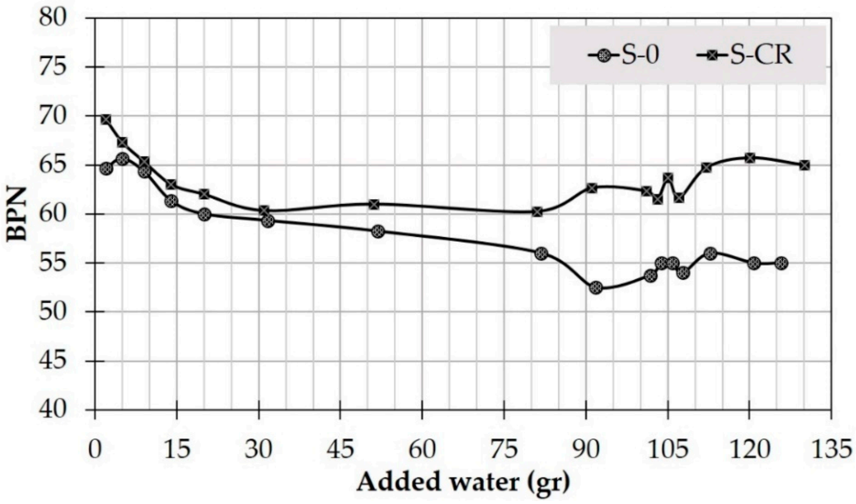

Figure 14. BPN levels during phase (5)—"water addition up to cleaning" for S-0 and S-CR specimens.

Based on the related findings, it seems that the CR addition in the asphalt mixture did not negatively influence the skid resistance performance in terms of BPN due to the various changes in the simulated conditions. Instead, it seems that BPN increased by almost 10% for S-CR in comparison to S-0 for all phases of the simulation, except for phase (2), where a slight decrease of ~4% was observed for S-CR.

Remarkably, the addition of water during phase (5) reduced the BPN levels for both specimens. This is a reasonable finding considering that after a prolonged dry period, as simulated in phase (3), the first shower (i.e., initial water drops of the wetting process) can create a very slippery road surface, a case that has been described in the international literature as "summer ice" [40]. In real weather conditions, this case can be very dangerous for moving vehicles, as a contaminated road surface is very slippery when it first becomes wet. Despite the washing off due to the addition of extra water (i.e., the end of the testing in Figure 14), the BPN levels remained lower at the end of the test compared to those of phase (2)—"water on clean surface". This probably occurred because the additional water rinses did not completely "wash and clean" the surface aggregates from the initial dry contamination.

4.2. HMA-RAP Mixtures

Figure 15 presents the effect of the temperature changes comparatively. It is obvious that the increase from 10 to 25 °C and from 25 to 30 °C reduced the BPN levels.

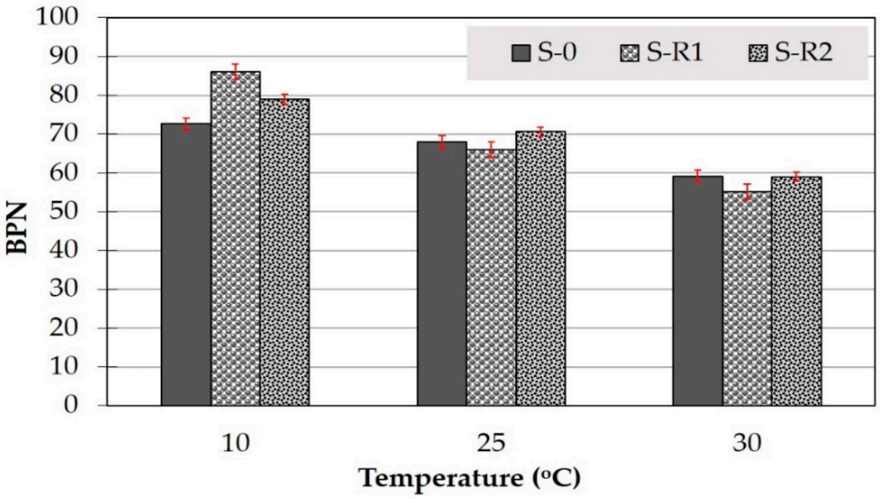

Figure 15. Temperature effect on the HMA-RAP specimens.

However, at 10 °C, the addition of RAP seemed to produce significant variations in the BPN levels amongst the specimens. There are two reasons for these results. First, the tested specimens are non-polished (non-trafficked), an issue that is detrimental, especially for the surface aggregates of S-0, which are masked by a film of asphalt bitumen (masking effect). Thus, the microtexture was not fully revealed in S-0. For S-R1 and S-R2 though, the presence of RAP aggregates that are polished to some extent (because they were part of an existing surface course before rehabilitation) in conjunction with the low addition of virgin asphalt implies that the revealed microtexture may vary. In addition, at low temperatures, the BPT slider is stiffer and more elastic due to the slider's viscoelastic nature and thus, more energy is needed (generation of hysteresis) for the slider to capture the profile of the aggregates (i.e., microtexture) [42]. Hence, the gripping action of the BPT slider, which is dependent on the surface microtexture, is amplified when the temperature decreases [42,62].

In terms of the macrotexture, the relationship between the air voids and skid resistance is illustrated in Figure 16 for each temperature and achieved air void content (S-0: 10.9%, S-R1: 7.7%, and S-R2: 7.9%). Sharper differences in the BPN levels were observed for the lowest temperature tested. Again, at low temperatures, the BPT slider becomes stiffer, so a specimen with an increased air void content, which corresponds practically to a rougher surface (i.e., improved macrotexture), makes it more difficult for the slider to bypass its surface (generation of adhesion). In other words, more energy is dissipated, resulting in higher BPN values [42,62]. Therefore, the difference in the air void content appears to be more critical at lower temperatures. Hence, both texture profile components appear to critically affect the BPN values at low temperatures.

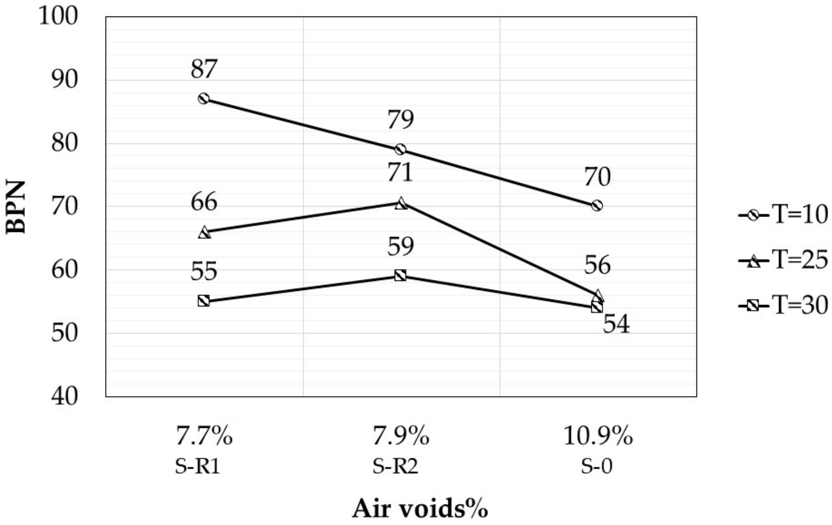

Figure 16. BPN in relation to the air void content and temperature.

With respect to the simulation of the weather conditions, Figures 17 and 18 show the effect of the water additions and contamination according to the implemented protocol. For the HMA-RAP specimens, the amount of the total added water was much lower than in the case of the S-CR specimen (<35 g, in total), simulating, in this case, a shorter event of water additions. It is noted that phase (4)—"wet contamination" was simulated for the HMA-RAP specimens instead of phase (3)—"dusty contamination". Again, the variance in each measurement stage of phase (5) was tolerable, so error bars were not added in Figure 18.

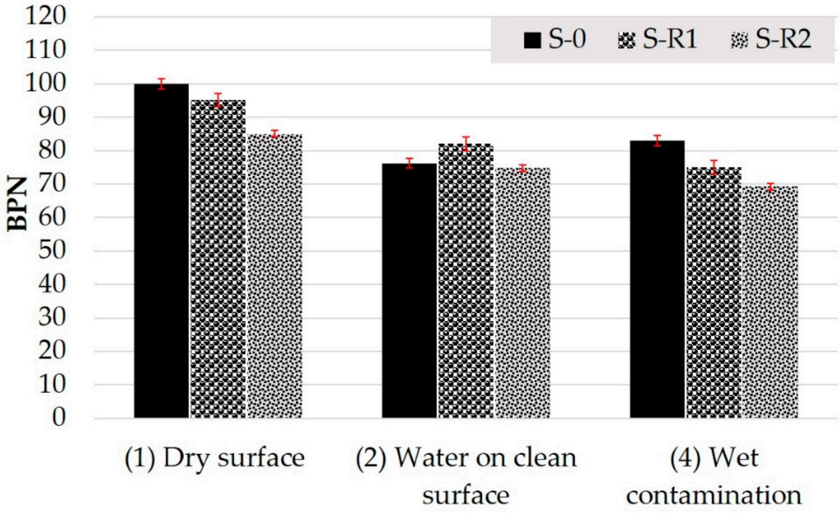

Figure 17. BPN levels during phases (1), (2), and (4) for the S-0, S-R1, and S-R2 specimens.

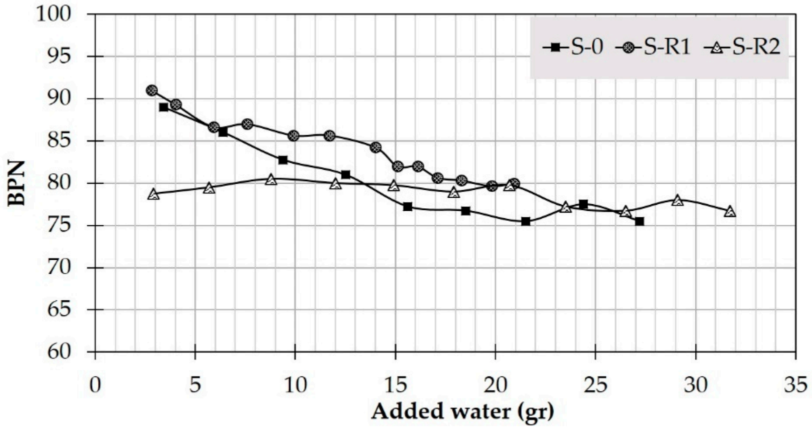

Figure 18. BPN levels during phase (5)—"water addition up to cleaning" for the S-0, S-R1, and S-R2 specimens.

Among the specimens, S-R2 exhibited the lowest BPN levels for phases 1, 2, and 4 compared to S-0 and S-R1. The low air void content of S-R2 in conjunction with the presence of fine RAP aggregates (i.e., poor microtexture) imply that the added water could not effectively penetrate into the specimen, something that accounts for the low BPN records. The S-R1 specimen exhibited higher skid resistance, providing an increased potential of this mixture to maintain skid resistance in wetting conditions. Furthermore, it seems that when the first amount of water was added during phase (5)—"water addition up to cleaning", the BPN levels increased compared to phase (4)—"wet contamination" for all specimens tested. This phenomenon (i.e., the comparison of phase (4) and the initiation of phase (5)) is probably explained by the development of the capillary pressure between the wet asperities of the mixture used for simulating contamination and the asperities of the asphalt mixture aggregates [63].

In other words, by adding a small amount of water, capillary bonds were formed that caused strong attraction amongst the aggregates, thereby increasing the resistance against the load of the BPT slider. This means that the BPT slider lost more energy in an effort to develop friction and consequently, the measurement of the BPN value was higher. According to Figure 7, a low angle of the BPT arm corresponds to a higher BPN measurement as more kinetic energy is dissipated for the development of friction. The addition of extra water during phase (5)—"water addition up to cleaning" led to the proportional break of these capillary bonds as the wet contamination became more saturated and entered the air voids or was bypassed by the movement of the BPT slider.

Moreover, the fact that contamination entered the air voids led to trapped contamination that blocked the water runoff (as explained illustratively in Figure 19). As a result, the BPN levels did not change remarkably, especially for S-R2, where the air void content was low and fine RAP particles were used. Therefore, water additions were continued for S-R2, although the stoppage criterion for phase (5) (i.e., dBPN < ±2 BPN) was met earlier enough based on Figure 18. Visual inspection of the specimen's surface during testing necessitated the continuation of the experiment. Indeed, after some extra water additions, BPN was found to slightly increase (i.e., a slow rate of runoff). On the contrary, the S-0 and S-R1 specimens did not appear to suffer from trapped contaminants probably because of the higher air voids and the absence of fine RAP particles, respectively, resulting in shorter testing events during phase (5). Finally, phase (5) was overall shorter for the HMA-RAP mixtures compared to the HMA-CR mixtures (Figure 14) because in phase (5) of the latter case, the contamination was dry, something that necessitated additional effort (i.e., longer testing events) for an effective wash off of the dusty contamination.

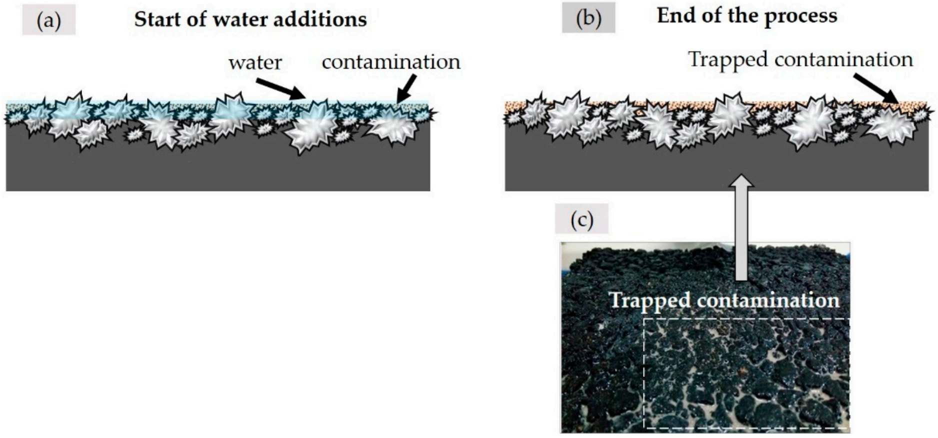

Figure 19. Wetting process: (**a**) start, (**b**) end and (**c**) slab status at the end of wetting process.

By the end of the testing for all HMA-RAP specimens, it can be seen that phase (5) produced nearly equal BPN levels to those observed in phase (2), since the asperities of the aggregates (i.e., microtexture) were almost clean because of the added wet contamination. Nevertheless, the issue of blocking of the water runoff may be detrimental to the provided macrotexture of the surface and this can be considered as a limitation of the BPT device as discussed in the following section.

5. Limitations of the Laboratory Process

It is worth noting that potential field-related factors affecting skid resistance cannot be fully accounted for in laboratory-scale testing. Undoubtedly, in a field-scale approach, there are factors related to weather conditions (e.g., an abrupt increase in the water film because of intense rainfalls or temperature fluctuations, etc.) that cannot be accurately simulated in the laboratory. However, it is believed that the present study sheds light on some critical cases and serves as a preliminary step for possible future field studies aiming to improve the performance evaluation compared to the current laboratory results.

In addition, the BPT device used in this study cannot fully simulate tire–road contact, as real vehicle tires are much rougher to provide better grip on the pavement surface. BPN measurements are known to be affected more by the microtexture component of skid resistance than the macrotexture. This problem could have led to slight changes in the skid resistance values, especially in cases where entrapped aggregates in the HMA-RAP specimens clogged the voids or macrotexture, which could not be detected by BPT. However, when vehicles move at low speeds on wet surfaces, microtexture has been shown to contribute more than macrotexture to providing tires with adequate grip for effective braking [64,65].

In addition, the fact that non-polished specimens were used for the present study is partially crucial for the results. More specifically, the film of bitumen covering the surface aggregates of the S-0 and S-CR specimens tends to reduce the microtexture, which is important for BPN measurements. This means that the results would likely have been different if polished samples were used. In fact, bitumen's "worn out" behavior due to the traffic impact can only be evaluated through a distinct dedicated laboratory testing simulating the polishing effect. The authors have already provided such an assessment [26] and for more complete insight, they plan to repeat the investigation of simulation of the weather conditions during several stages of the polishing process. This could enable more comprehensive definitions of the materials' behavior in terms of the skid resistance against weather changes. Nevertheless, the methodology used demonstrates a laboratory framework that is applicable to both non-polished and polished specimens when investigating the skid resistance potential due to weathering.

6. Conclusions and Future Prospects

Recycled materials seem to be attractive alternatives in pavement construction, especially when facing the maintenance challenges of LLPs, where the goal is to adopt sustainable practices for more effective infrastructure management. Since knowledge of the frictional performance of recycled materials is limited, the present study aimed to undertake a laboratory-scale investigation of the use of two types of recycled materials, specifically crumb rubber (CR) and RAP, in HMA surface courses. The experimental findings of this study can be summarized as follows:

From the laboratory investigation of the CR material:

- The fabricated CR-modified mixture (specimen: S-CR) performed similarly to the conventional one (specimen: S-0) as the temperature changed. An increase in the temperature from 15 to 25 °C caused a decrease in the BPN levels, probably due to the viscoelastic nature of both the asphalt mixture and the rubber compound of the BPT slider.
- The fabricated CR-modified mixture performed slightly better in terms of the measured BPN levels than the conventional one under almost all simulated weather variations. However, the addition of water to the dry and contaminated surfaces led to lower skid resistance values for both S-0 and S-CR. This aspect is probably related to the condition of "summer ice", which can occur in the field when a road surface first becomes wet after a prolonged dry period, resulting in a very slippery surface and dangerous driving conditions. As a result, by the end of the water additions, the BPN levels did not reach the corresponding ones of phase (2)—"water on clean surface", as the initially dry contamination could not be fully washed off.

From the laboratory investigation of the RAP material:

- An increase in the temperature was found to decrease the BPN levels. Amongst the fabricated HMA-RAP specimens, the impact of the RAP addition was found to be more pronounced in the lower tested temperature of 10 °C, where the RAP specimens performed better than the HMA specimen. This remark is probably connected with the fact that the HMA specimen was non-polished, and its surface aggregates were covered by asphalt bitumen that blocked the microtexture of the S-0. In addition, at this temperature, the impact of the air void content (expressing macrotexture) was found to be critical. On the contrary, almost equal BPN levels were found for the fabricated HMA-RAP specimens at higher temperatures.
- With respect to the simulated weather conditions, the S-0 and S-R1 specimens proved to have similar performances while the BPN levels in S-R2 (with fine RAP aggregates) were found to be lower.

- The initial addition of water to the wet contaminated surfaces caused an increase in the BPN level of the HMA-RAP specimens, a condition that was explained by the development of capillary bonds between the wet asperities of the contaminated mixture and the asperities of the asphalt mixture aggregates (i.e., when comparing phase (4) and the initiation of phase (5)). By adding extra water, the capillary bonds broke and the final BPN levels reached those corresponding to phase (2)—"water on clean surface", indicating an effective washing of the initial wet contamination.
- The low air voids and fine particles of the S-R2 specimen were detrimental to the formulation of trapped contamination, which clogged the voids between the aggregates and blocked water runoff.

In summary, the present study on recycled materials did not show any negative effects on skid resistance with respect to BPN. Moreover, it is considered that the results may add to the existing knowledge of the polishing behavior of mixtures containing such materials. Considering that weather conditions are becoming more critical nowadays due to worldwide climate change, the skid resistance of asphalt mixtures containing recycled materials should be systematically further researched. Despite the limited number of specimens tested, the procedure described here can serve as a preliminary methodological framework for exploring further aspects of the skid resistance potential of recycled materials. Therefore, different weather conditions were intentionally considered in order to obtain several preliminary insights that could indicate areas of improvement for the developed testing process.

Future research prospects for the authors include the joint consideration of the traffic and weather effects in a laboratory-scale environment with a wider spectrum of conditions (e.g., lower and higher temperatures than those tested and expansion of the wetting protocol to include additional temperatures), and an evaluation of the field performance of recycled materials on pilot road sections.

Author Contributions: Conceptualization, M.P. and C.P.; methodology, M.P. and C.P.; analysis, M.P. and C.P.; writing—original draft preparation, M.P.; review and editing, M.P. and C.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

APT	Accelerated Pavement Testing
BPN	British Pendulum Number
BPT	British Pendulum Tester
CR	Crumb Rubber
FHWA	Federal Highway Administration
HMA	Hot-Mix Asphalt
LLP	Long-Life Pavement
NTUA	National Technical University of Athens
RAP	Reclaimed Asphalt Pavement
S-0	Specimen with HMA only (reference specimen)
S-CR	Specimen with HMA and CR at 10%
S-R1	Specimen with HMA and RAP at 30%
S-R2	Specimen with HMA and RAP at 15%

References

1. Gáspár, L.; Bencze, Z. Long-life Pavements-European & American Perspectives. *New Build. Mater. Constr. World* **2018**, *24*, 122–135.
2. Ferne, B.; Nunn, M. The European Approach to Long Lasting Asphalt Pavements: A state-of-the-art review by ELLPAG. In Proceedings of the Paper Presentation in the International Conference on Perpetual Pavements, Columbus, OH, USA, 13–15 September 2006.
3. Newcomb, D. *Perpetual Pavements–A Synthesis*; Asphalt Pavement Alliance: Lanham, MD, USA, 2002.
4. Antunes, V.; Freire, A.C.; Neves, J. A review on the effect of RAP recycling on bituminous mixtures properties and the viability of multi-recycling. *Constr. Build. Mater.* **2019**, *211*, 453–469. [CrossRef]
5. Zhao, Y.; Goulias, D.; Peterson, D. Recycled Asphalt Pavement Materials in Transport Pavement Infrastructure: Sustainability Analysis & Metrics. *Sustainability* **2021**, *13*, 8071.
6. Tarsi, G.; Tataranni, P.; Sangiorgi, C. The Challenges of Using Reclaimed Asphalt Pavement for New Asphalt Mixtures: A Review. *Materials* **2020**, *13*, 4052. [CrossRef]
7. Shu, X.; Huang, B. Recycling of waste tire rubber in asphalt and Portland cement concrete: An overview. *Constr. Build. Mater.* **2014**, *67*, 217–224. [CrossRef]
8. Rathore, M.; Zaumanis, M.; Haritonovs, V. Asphalt Recycling Technologies: A Review on Limitations and Benefits. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *660*, 012046. [CrossRef]
9. Antunes, V.; Neves, J.; Freire, A.C. Performance Assessment of Reclaimed Asphalt Pavement (RAP) in Road Surface Mixtures. *Recycling* **2021**, *6*, 32. [CrossRef]
10. Ozer, H.; Yang, R.; Al-Qadi, I.L. Quantifying sustainable strategies for the construction of highway pavements in Illinois. *Transp. Res. Part D Transp. Environ.* **2017**, *51*, 1–13. [CrossRef]
11. Vandewalle, D.; Antunes, V.; Neves, J.; Freire, A.C. Assessment of Eco-Friendly Pavement Construction and Maintenance Using Multi-Recycled RAP Mixtures. *Recycling* **2020**, *5*, 17. [CrossRef]
12. Yu, X.; Zaumanis, M.; Dos Santos, S.; Poulikakos, L.D. Rheological, microscopic, and chemical characterization of the rejuvenating effect on asphalt binders. *Fuel* **2014**, *135*, 162–171. [CrossRef]
13. McDaniel, R.S.; Soleymani, H.; Anderson, R.M.; Turner, P.; Peterson, R. *Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method*; NCHRP Web Document 30; National Academies Press: Washington, DC, USA, 2000.
14. Copeland, A. *Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice*; No. FHWA-HRT-11-021; Federal Highway Administration: McLean, VA, USA, 2011.
15. Karlsson, R.; Isacsson, U. Material-related aspects of asphalt recycling–state-of-the-art. *J. Mater. Civ. Eng.* **2006**, *18*, 81–92. [CrossRef]
16. Antunes, V.; Freire, A.C.; Neves, J. Investigating aged binder mobilization and performance of RAP mixtures for surface courses. *Constr. Build. Mater.* **2021**, *271*, 121511. [CrossRef]
17. Gottumukkala, B.; Kusam, S.R.; Tandon, V.; Muppireddy, A.R.; Mullapudi, S.R. Restriction of RAP% in HMA Based on Aggregate Gradation and Binder Properties. *Civ. Eng.* **2021**, *2*, 811–822. [CrossRef]
18. Lo Presti, D. Recycled Tyre Rubber Modified Bitumens for road asphalt mixtures: A literature review. *Constr. Build. Mater.* **2013**, *49*, 863–881. [CrossRef]
19. Venudharan, V.; Biligiri, K.P.; Sousa, J.B.; Way, G.B. Asphalt-rubber gap-graded mixture design practices: A state-of-the-art research review and future perspective. *Road Mater. Pavement Des.* **2017**, *18*, 730–752. [CrossRef]
20. European Tire & Rubber Manufacturer's Association (ETRMA). *The ETRMA Statistics Report*; European Tire & Rubber Manufacturer's Association: Saint-Josse-ten-Noode, Belgium, 2019.
21. Bressi, S.; Fiorentini, N.; Huang, J.; Losa, M. Crumb rubber modifier in road asphalt pavements: State of the art and statistics. *Coatings* **2019**, *9*, 384. [CrossRef]
22. Sousa, J.B.; Vorobiev, A.; Rowe, G.M.; Ishai, I. Reacted and Activated Rubber: Elastomeric Asphalt Extender. *Transp. Res. Rec.* **2013**, *2371*, 32–40. [CrossRef]
23. Kedarisetty, S.; Biligri, K.P.; Sousa, J.B. Advanced rheological characterization of Reacted and Activated Rubber (RAR) modified asphalt binders. *Constr. Build. Mater.* **2016**, *122*, 12–22. [CrossRef]
24. Bressi, S.; Santos, J.; Giunta, M.; Lo Presti, D. A comparative environmental assessment of asphalt mixtures for railway sub-ballast containing alternative materials. *Resour. Conserv. Recycl.* **2018**, *137*, 76–88. [CrossRef]
25. Moreno, F.; Rubio, M.; Martinez-Echevarria, M. Analysis of digestion time and the crumb rubber percentage in dry-process crumb rubber modified hot bituminous mixes. *Constr. Build. Mater.* **2001**, *25*, 2323–2334. [CrossRef]
26. Pomoni, M.; Plati, C.; Kane, M.; Loizos, A. Polishing behaviour of asphalt surface course containing recycled materials. *Int. J. Transp. Sci. Technol.* 2021. [CrossRef]
27. Chu, L.; Zhou, B.; Fwa, T.F. Directional characteristics of traffic polishing effect on pavement skid resistance. *Int. J. Pavement Eng.* 2021. [CrossRef]
28. Flintsch, G.W.; McGhee, K.K.; de Leon Izeppi, E.; Najafi, S. The Little Book of Tire Pavement Friction. In *Pavement Surface Properties Consortium*; Version 1.0; Virginia Tech: Blacksburg, VA, USA, 2012.
29. Azzam, A.; Ali Khasawneh, M.; Al-Omari, A.A.; Masad, E.; Kassem, E. A statistical approach for predicting skid resistance of asphalt pavements. *Int. J. Pavement Res. Technol.* **2021**, *14*, 647–654. [CrossRef]

30. World Health Organization. Global status report on road safety 2018. *Licence: CC BYNC- SA 3.0 IGO, Geneva.* 2018. Available online: https://www.who.int/publications/i/item/9789241565684 (accessed on 14 April 2022).
31. Pomoni, M.; Plati, C.; Loizos, A.; Yannis, G. Investigation of pavement skid resistance and macrotexture on a long-term basis. *Int. J. Pavement Eng.* **2022**, *23*, 1060–1069. [CrossRef]
32. Wang, A.; Shena, S.; BoSong, X. Micro-surfacing mixtures with reclaimed asphalt pavement: Mix design and performance evaluation. *Constr. Build. Mater.* **2019**, *201*, 303–313. [CrossRef]
33. Eskandarsefat, S.; Sangiorgi, C.; Dondi, G.; Lamperti, R. Recycling asphalt pavement and tire rubber: A full laboratory and field scale study. *Constr. Build. Mater.* **2018**, *176*, 283–294. [CrossRef]
34. Doyle, J.; Howard, I. Laboratory Assessment of Skid Resistance for High RAP Content Warm Mixed Asphalt. In Proceedings of the Geo-Frontiers Congress: Advances in Geotechnical Engineering, ASCE library, Dallas, TX, USA, 13–16 March 2011; pp. 4515–4524.
35. Putra, A.D.; Hadiwardoyo, S.P.; Sumabrata, R.J. Skid resistance performance against temperature change of hot-mix recycled asphalt pavement with added crumb rubber. *AIP Conf. Proc.* **2019**, *2114*, 04112. [CrossRef]
36. Plati, C.; Pomoni, M. Impact of Traffic Volume on Pavement Macrotexture and Skid Resistance Long-Term Performance. *Transp. Res. Rec.* **2019**, *2673*, 314–322. [CrossRef]
37. Fwa, T.F. Skid resistance determination for pavement management and wet-weather road safety. *Int. J. Transp. Sci. Technol.* **2017**, *6*, 217–227. [CrossRef]
38. van Bijsterveld, W.; del Val, M.A. Towards quantification of seasonal variations in skid resistance measurements. *Road Mater. Pavement Des.* **2016**, *17*, 477–486. [CrossRef]
39. Plati, C.; Pomoni, M.; Stergiou, T. From Mean Texture Depth to Mean Profile Depth: Exploring possibilities. In *Proceedings of the 7th International Conference on Bituminous Mixtures and Pavements (ICONFBMP)*; Nikolaides, A.F., Manthos, E., Eds.; CRC Press: London, UK, 2019; pp. 639–644. [CrossRef]
40. Wilson, D.J. An Analysis of the Seasonal and Short-Term Variation of Road Pavement Skid Resistance. Ph.D. Thesis, The University of Auckland, Auckland, New Zealand, 2006.
41. Do, M.-T.; Tang, Z.; Kane, M.; de Larrard, F. Pavement polishing–development of a dedicated laboratory test and its correlation with road results. *Wear* **2007**, *263*, 36–42. [CrossRef]
42. Xie, X.; Lu, G.; Liu, P.; Zhouc, Y.; Wang, D.; Oeser, M. Influence of temperature on polishing behaviour of asphalt road surfaces. *Wear* **2018**, *402–403*, 49–56. [CrossRef]
43. Anupam, K.; Srirangam, S.K.; Scarpas, A.; Kasbergen, C. Influence of temperature on tire-pavement friction: Analyses. *Transp. Res. Rec.* **2013**, *2369*, 114–124. [CrossRef]
44. Nataadmadja, A.D.; Wilson, D.J.; Costello, S.B.; Do, M.-T. Correlating Laboratory Test Methodologies to Measure Skid Resistance of Pavement Surfaces. *Transp. Res. Rec.* **2015**, *2506*, 107–115. [CrossRef]
45. *ASTM D3515-01*; Standard Specification for Hot-Mixed, Hot-Laid Bituminous Paving Mixtures. ASTM International: West Conshohocken, PA, USA, 2001.
46. *European Standard EN 13108-01*; Bituminous Mixtures-Material Specifications-Part 1: Asphalt Concrete. European Standard: Brussel, Belgium, 2016.
47. *European Standard EN 1426*; Bitumen and Bituminous Binders-Determination of Needle Penetration. European Standard: Brussel, Belgium, 2015.
48. *European Standard EN 1427*; Bitumen and Bituminous Binders-Determination of the Softening Point-Ring and Ball Method. European Standard: Brussel, Belgium, 2015.
49. *European Standard EN 13398*; Bitumen and Bituminous Binders. Determination of the Elastic Recovery of Modified Bitumen. European Standard: Brussel, Belgium, 2017.
50. *European Standard EN 15326*; Bitumen and Bituminous Binders-Measurement of Density and Specific Gravity-Capillary-Stoppered Pyknometer Method. European Standard: Brussel, Belgium, 2009.
51. *European Standard EN 12697-34*; Bituminous Mixtures-Test Methods-Part 34: Marshall Test. European Standard: Brussel, Belgium, 2020.
52. *ASTM D3203/D3203M-17:*; Standard Test Method for Percent Air Voids in Compacted Asphalt Mixtures. ASTM International: West Conshohocken, PA, USA, 2017.
53. *European Standard EN 12697-12*; Bituminous Mixtures-Test Methods-Part 12: Determination of the Water Sensitivity of Bituminous Specimens. European Standard: Brussel, Belgium, 2018.
54. *European Standard EN 12697-06*; Bituminous Mixtures. Test Methods for Hot Mix Asphalt-Determination of Bulk Density of Bituminous Specimens. European Standard: Brussel, Belgium, 2020.
55. *European Standard EN 12697-33*; Bituminous Mixtures—Test Method—Part 33: Specimen Prepared by Roller Compactor. European Committee for Standardization (CEN): Brussels, Belgium, 2019; p. 22.
56. *ASTM D2172-95*; Standard Test Methods for Quantitative Extraction of Bitumen from Bituminous Paving Mixtures. ASTM International: West Conshohocken, PA, USA, 2017.
57. *ASTM E303-93*; Standard Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester. ASTM International: West Conshohocken, PA, USA, 2018.

58. Hichri, Y.; Cerezo, V.; Do, M.-T. Effect of dry deposited particles on the tire/road friction. *Wear* **2017**, *376–377*, 1437–1449. [CrossRef]
59. Wang, T.; Hu, L.; Pan, X.; Xu, S.; Yun, D. Effect of the Compactness on the Texture and Friction of Asphalt Concrete Intended for Wearing Course of the Road Pavement. *Coatings* **2020**, *10*, 192. [CrossRef]
60. Al-Assi, M.; Kassem, E. Evaluation of Adhesion and Hysteresis Friction of Rubber–Pavement System. *Appl. Sci.* **2017**, *7*, 1029. [CrossRef]
61. Bianchini, A.; Heitzman, M.; Maghsoodloo, S. Evaluation of Temperature Influence on Friction Measurements. *J. Transp. Eng.* **2011**, *137*, 640–647. [CrossRef]
62. Wu, J.; Wang, X.; Wang, L.; Zhang, L.; Xiao, Q.; Yang, H. Temperature Correction and Analysis of Pavement Skid Resistance Performance Based on RIOHTrack Full-Scale Track. *Coatings* **2020**, *10*, 832. [CrossRef]
63. Guo, F.; Tian, Y.; Liu, Y.; Wang, Y. Unexpected friction behaviours due to capillary and adhesion effects. *Sci. Rep.* **2017**, *7*, 148. [CrossRef]
64. Yu, M.; You, Z.; Wue, G.; Kong, L.; Liu, C.; Gao, J. Measurement and modeling of skid resistance of asphalt pavement: A review. *Constr. Build. Mater.* **2020**, *260*, 119878. [CrossRef]
65. Hall, J.W.; Smith, K.L.; Titus-Glover, L.; Wambold, J.C.; Yager, T.J.; Rado, Z. Guide for Pavement Friction (Contractor's Final Report for NCHRP Project 01-43). NCHRP Web-only document 108. In *Transportation Research Board (TRB) Publication*; Transportation Research Board (TRB) of the National Academies: Washington, DC, USA, 2009.