infrastructures

Article

Investigating the Ability of Road Specifications to Discriminate the Rutting Behavior of Rubberized Asphalt Mixtures in Italy †

Usman Ghani [1], Silvia Milazzo [1], Gaspare Giancontieri [1], Gabriella Buttitta [1], Fan Gu [2] and Davide Lo Presti [1,*]

[1] Department of Engineering, University of Palermo, Viale Delle Scienze, 90128 Palermo, Italy
[2] School of Traffic & Transportation Engineering Changsha, University of Science and Technology, Changsha 410114, China
* Correspondence: davide.lopresti@unipa.it
† Full length article of conference proceedings presented at MAIREINFRA2023, Honolulu, HI, USA, 16–19 August 2023.

Abstract: Despite its worldwide adoption in many countries, rubberized asphalt mixtures are not fully incorporated as an alternative paving material in current Italian road specifications. This reluctance stems from a lack of experience, resistance to change in established work practices, and, sometimes, insufficient evidence demonstrating tangible benefits with local specifications. Furthermore, conventional characterization methods such as void checks and indirect tensile strength testing by means of IDT may not accurately capture the true benefits of using alternative paving materials. This study introduces performance-driven characterization approaches with the final aim of evaluating whether more advanced procedures may provide additional information compared to current practices and, in turn, promote the use of alternative paving materials. Hence, an investigation has been conducted to compare the rutting behavior of conventional asphalt mixtures with those modified with engineered crumb rubber (ECR). This comparison utilized performance-driven characterization approaches, including a basic IDT-based methodology at higher temperatures (HT-IDT), as well as two more sophisticated approaches, the Stress Sweep Rutting (SSR) and Flow Number (FN) tests, using the asphalt mixture performance tester (AMPT). Finally, the results were compared with those obtained using the IDT, a conventional method as specified by the major Italian road authority. As a result, the addition of ECR proves beneficial in enhancing the qualities of dense mixtures tailored for use on urban and secondary roads; however, only performance-driven characterization, with both basic and advanced methodologies, can clearly describe the pivotal role of ECR in achieving discernible enhancements in the rutting behavior of asphalt mixtures.

Keywords: rutting; permanent deformation; performance-related characterization; tire rubber; modified asphalt mixtures; SSR; HT-IDT; shift model

Citation: Ghani, U.; Milazzo, S.; Giancontieri, G.; Buttitta, G.; Gu, F.; Presti, D.L. Investigating the Ability of Road Specifications to Discriminate the Rutting Behavior of Rubberized Asphalt Mixtures in Italy. *Infrastructures* **2024**, *9*, 113. https://doi.org/10.3390/infrastructures9070113

Academic Editors: Hosin "David" Lee and Tatiana García-Segura

Received: 30 May 2024
Revised: 11 July 2024
Accepted: 16 July 2024
Published: 18 July 2024

1. Introduction

In recent times, there has been a notable rush in the pavement sectors to focus on enhancing construction methodologies, aiming to extend the lifespan of pavements and reduce the impacts associated with maintenance and rehabilitation efforts. These efforts are primarily associated with numerous failures occurring in flexible pavements. Several research investigations have explored diverse methods of forecasting fundamental failure mechanisms in flexible pavements, such as rutting occurrence [1,2]. Rutting can be defined as the occurrence of transverse displacement caused by depression in a surface along the longitudinal direction. As a result of heavy traffic loads, the volumetric and shear strain accumulation results in permanent deformation/rutting [3]. Ultimately, it involves the compression of the road's layers, which leads to with or without a change in volume, and shear deformation. These effects result from the continual application of traffic loads and adverse temperature conditions [4]. The main mechanism of permanent deformation inside the flexible pavement structure is mainly based on three nodes, i.e., material loss, plastic flow in the lateral direction, and densification [3,5].

One form of non-structural rutting, specifically an asphalt mixture rutting, occurs because of service failures, when the pavement experiences an ample amount of traffic load and an increase in temperature [6]. In such cases, the asphalt material exhibits an immediate elastic response, followed by progressively increasing deformation over time. This irreversible distress not only deteriorates the comfort of the ride and heightens the potential for safety issues but also diminishes the longevity of the pavement, leading to elevated maintenance expenses [7]. For example, the presence of rutting poses a safety hazard, especially when the ruts are filled with water, as this can lead to vehicle hydroplaning. This phenomenon, where vehicles lose complete contact with the road surface, poses an immediate risk of sliding out of the designated lane, creating a potentially dangerous situation [8–10]. An essential aspect in designing a flexible pavement involves material characterization to ensure reliable predictions of permanent deformation [11–13]. At present, the material characterization procedure involves the examination of various modified materials incorporated into asphalt mixes through diverse laboratory experiments. This approach establishes a robust basis for assessing the mechanical properties of asphalt mixes, particularly with respect to permanent deformation [14,15]. Several researchers have suggested different types of physical and chemical modifiers to be used in asphalt mixtures, enhancing the pavement's rutting resistance behavior. These diverse types of modifiers like fillers, polymers, plastics, and rubbers along with anti-rutting agents are widely available but are not fully implemented because of the complex issues associated with their cost and construction on-site [16–18].

One common type of these modifiers is a crumb rubber that can be obtained through the recycling process of waste tires. This prevalent modifier is utilized in asphalt mixes [19]. Currently, technological advancements involve the integration of both synthetic and recycled rubber into traditional asphalt mixes to improve the resistance to rutting [20,21]. This approach has demonstrated effectiveness in improving the cracking resistance and has also been found to be economical for road construction against other synthetic polymers used in modifying asphalt mix properties [19]. However, due to the swelling at high temperatures, crumb rubber is less likely to resist permanent deformation [22,23]. Another alternative is engineered crumb rubber (ECR), which is a commercial product treated chemically to manage swelling in asphalt mixtures and reduce operational temperatures during mixing and compaction phases. The patented ECR product, developed in the United States and now also distributed in Europe, is introduced into asphalt mixtures using a dry process [24]. Since 2021, Italian specifications (ANAS, 2021) have incorporated rubberized asphalt mixtures in their guidelines [25]. These specifications are not fully implemented and have a lack of performance-related characterization, especially in terms of the rutting behavior of asphalt mixes. The Italian road authorities currently rely on conventional IDT testing at 25 °C, which is unable to characterize the rutting behavior at high temperatures. The predominant factors contributing to this situation are insufficient information and training among professionals and stakeholders, as well as a lack of support from local policies.

In addition to the integration of various modifiers into asphalt mixtures, a variety of testing methodologies and equipment are available to evaluate the resistance to permanent deformation. These include rutting evaluation through wheel tracker equipment, an asphalt pavement analyzer, HT-IDT testing, and SSR testing using AMPT [16,26,27]. These different testing methodologies vary in complexity and cost-related issues, but are designed to simulate the conditions of a pavement subjected to heavy traffic loads and challenging environmental conditions. Nevertheless, compliance requirements set by the Italian road authority still rely on volumetric properties like void content checks and mechanical parameters, such as IDT at 25.0 °C. These requirements are unable to include any characterization methods specifically designed to evaluate resistance to permanent deformation. Another issue related to the specifications of the Italian road authority is the laboratory compaction of the asphalt mixtures. These specifications are based on achieving a certain number of gyrations based on the energy compaction process. However, performance-related characterization is based on achieving a specific height and targeting the specific air void content of the compacted asphalt mixtures [25,28]. The basic approach of this study with regard to rutting characterization has an advantage in terms of characterizing the rutting based on low-cost and easily available equipment at different research laboratories. Meanwhile, the advanced approach considered the climate conditions to characterize the rutting behavior of the conventional and rubberized asphalt mixes. It is notable that the regions that match the climatic conditions of Sicily do not require any climatic data in the shift model for rutting characterization.

Aim of the Study

To address the aforementioned research gaps concerning material advancement and testing methodologies used by the Italian road authorities, this study aims to evaluate the ability of current Italian road specifications to discriminate the rutting behavior of conventional and rubberized asphalt mixtures. Moreover, this research study proposes two approaches, i.e., Basic and advanced level, based on the availability of the equipment in research laboratories around the globe for the better quantification of the permanent deformation of alternative paving materials.

In this regard, an experimental program was employed with a multi-level strategy, incorporating conventional characterization that includes volumetric (by means of void content analysis) and mechanical characterization (by means of IDT testing at 25.0 °C). The alternative method includes laboratory compaction that targets the 5.0% air voids and additional characterization based on basic- and advanced-level testing of asphalt mixtures for their rutting behavior. The basic-level testing includes an HT-IDT test at 54.0 °C. Additionally, FN and SSR tests were carried out for advanced performance-based viscoplastic characterization. The outcomes of both approaches have been tailored to the climatic conditions observed in the Sicily region of Italy. The organization of this research study is based on the following sections. Section 1 provides a brief introduction on the background of permanent deformation and the level of research already carried out on different alternative paving materials and testing methodologies The aim of the study has also been highlighted in this section. Section 2 provides the details of materials and methodology of this study. While Section 3 provides details about the results and discussions from QA/QC by the Italian road authorities to additional rutting characterization. Section 4 provides a summary of the results including a comparison of the conventional and rubberized asphalt mixtures and also a discrimination between the testing methodologies for the evaluation of permanent deformation. This section also highlights the comparison of the laboratory compaction processes based on energy compaction and target air void studies. The conclusion, results, and final recommendations to practitioners for the use of rubberized asphalt mix and the adaptation of testing methodologies are provided in Section 5.

2. Materials and Methods

2.1. Materials

The asphalt mixtures examined in this study were formulated in a laboratory setting specifically for surface courses, designed for urban areas with low traffic volumes, following the guidelines of the Italian road authority [25]. Two compositions of mixtures were analyzed, namely, conventional asphalt concrete, identified as “AC8 CONV”, and rubberized asphalt mix, referred to as “AC8 ECR”. The designated maximum aggregate size was 8.0 mm for both the conventional and rubberized asphalt compositions. AC8 ECR is a rubberized asphalt mixture produced by incorporating engineered crumb rubber (ECR) through a dry process where the rubber is added to the mixer as an additional fine particle. ECR is an innovative rubber chemically treated to prevent excessive swelling during laying and compaction operations. It also aids in improving the pavement’s life cycle with lower maintenance. The addition of ECR in asphalt mixes ranges from proportions of 0.5 to 1.5% by weight of the total mixture weight [20]. The grading characteristics of both the conventional and rubberized mix are highlighted in Figure 1, respectively. The gradation curve was adopted from "USURA B" Italian specifications for wearing surfaces [25,29]. As can be seen in Figure 1, AC8 ECR is covering almost all the sieve sizes and has a finer gradation for wearing surfaces.

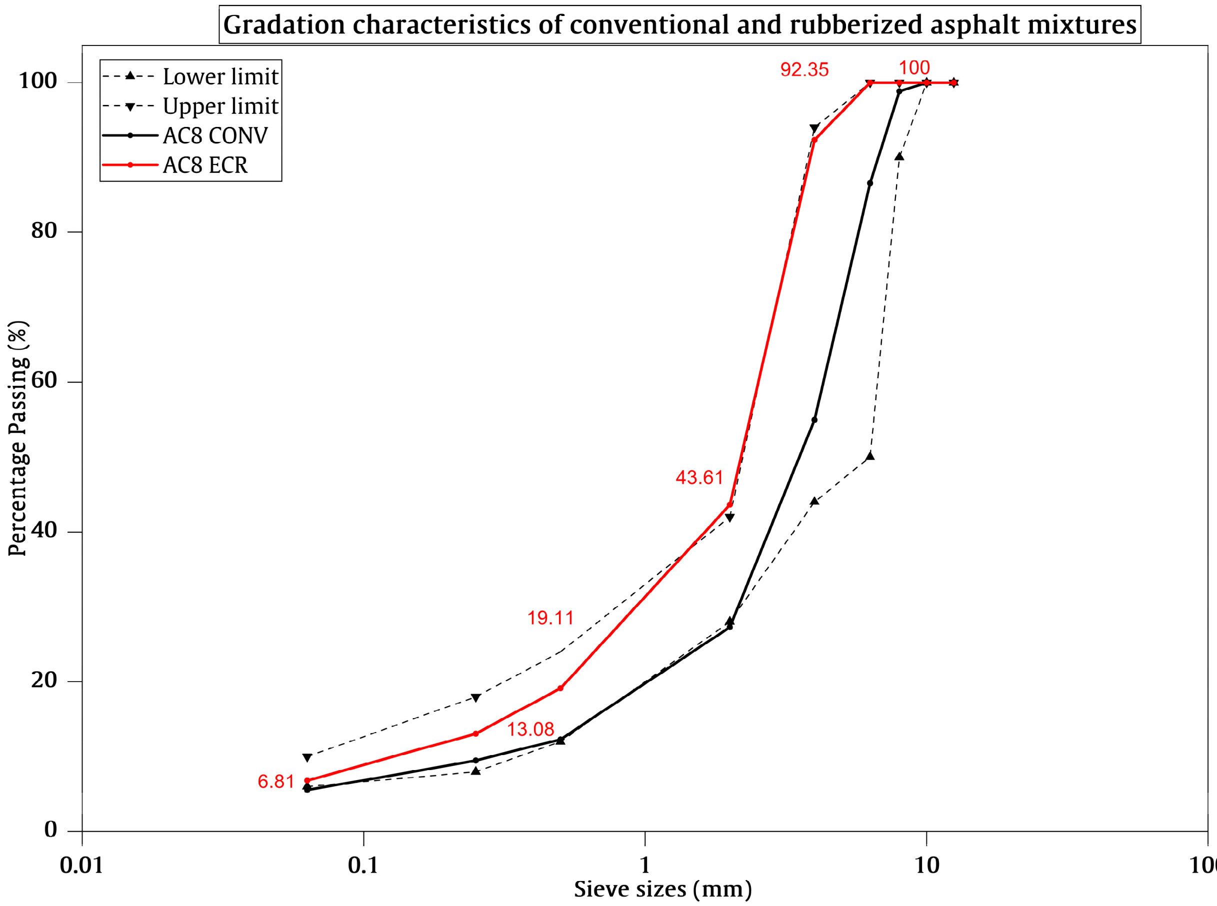

Figure 1. Gradation curve of conventional and rubberized mixes.

Specimen Preparation

The mixture composition is summarized in Table 1. The specimens were produced using a gyratory compaction method, applying a vertical pressure of 600 kPa [30]. The compaction process involved a gyration speed of 30.0 rpm, an external gyration angle set at 1.25°, and utilized a mold with a diameter of 150 mm. Two compaction methods were adopted, based, respectively, on compaction energy and target air void studies. The first method involved energy compaction to check the air void content of the mixtures and to ensure compliance with the Italian road authority (ANAS) [31]. The air void contents were determined using a hydrostatic process according to UNI EN 12697-5 [32]. After successful compliance of the mixes, the second compaction method was carried out by targeting 5.0% air voids for performance-based characterization, using a height of 180.0 mm as required for advanced laboratory testing [33,34]. For conventional and basic-level characterization that includes IDT testing, the dimensions of the specimen were 50 mm (height) × 100 mm (diameter). After achieving the targeted mass of the 5.0% air voids, the new Superpave gyratory specimens were compacted and were cored and cut to obtain the dimensions necessary to carry out the basic and advanced laboratory tests.

Table 1. Composition of mixtures.

Mixtures	Binder Type	Asphalt Binder Content (%)	Rubber Content (%)	Target Air Voids (%)
AC8 CONV	50/70	4.80	-	5.0
AC8 ECR	50/70	5.20	0.50	5.0

2.2. Methods

The conventional and rubberized asphalt mixes were first checked to ensure the compliance with the Italian road authority. Conventional characterization is based on void content checks and IDT testing starting from 20 ± 5 °C. The air void content range for a certain number of gyrations can be seen in Table 2. Once the mixes were found to comply with the Italian standards, the methodology was further extended for performance-related characterization in terms of the rutting behavior, using AC8 CONV conventional mix and AC8 ECR rubberized mix by targeting the 5.0% air voids in both mixes.

Table 2. Benchmark values for conventional characterization.

Characterisation	Property	Benchmark Values		Standards/Specifications	Reference (s)
Conventional (QA/QC—Italian road authorities)	Void content check	No. of gyrations	Void content (%)	UNI EN 12697-5/ANAS	[25]
		N10	11–15		
		N120	3–6		
		N210	≥2		
	Indirect tensile strength at 25.0 °C	ITS (MPa)	0.72–1.60	UNI EN 12697-23/ANAS	[25]
		ITS (MPa)	≥0.6		
	Indirect tensile coefficient at 25.0 °C	CTI (MPa)	≥65	UNI EN 12697-23/ANAS	[25]
		CTI (MPa)	50–150		

Performance-related characterization (PRC) on a basic level was carried out with HT-IDT at 54.0 °C. However, FN tests at 54.0 °C and SSR tests at a low temperature of 20.0 °C and a high temperature of 54.0 °C were conducted to characterize the mixes on an advanced level.

Each approach exhibited an increasing level of intricacy for assessing the rutting resistance of the conventional and rubberized asphalt mixtures. The experimental procedure is shown in Figure 2.

2.2.1. Conventional Characterization (QA/QC—Italian Road Authority Requirements)

Conventional IDT Testing

Conventional characterization involves the completion of an IDT test. The IDT test was carried out using UNI EN 12697-23 at 25.0 °C; three trials were conducted for each examined mixture [25]. At this temperature, there was no need to modify the specimens for further conditioning. Referring to Table 2, the ANAS Italian road specifications for quality assurance and quality control (QA/QC) recommend a minimum tensile strength between 0.72 and 1.60 MPa for asphalt mixtures, while the ANAS CSA ACUSTICA (QA/QC) specification recommend a minimum range of greater than or equal to 0.6 MPa. The peak load at the specimen's fracture and its dimensions are used to compute the ITS, as indicated by Equation (1).

The formula for indirect tensile strength (ITS) is expressed as

$$\text{ITS} = 2P/(\pi DH) \quad (1)$$

Here, P stands for the peak load, H denotes the specimen's height, and D indicates the diameter of the specimen.

The indirect tensile coefficient (CTI) of both the mixtures was calculated by the formula in Equation (2) [25]. The minimum range recommended by the ANAS for the CTI is greater than or equal to 65 MPa, while for the ANAS CSA ACUSTICA, the minimum recommended range is between 50 and 150 MPa.

$$CTI = \pi.ITS.D/2.\ \delta_V \tag{2}$$

Here, in Equation (2), δ_V represents the vertical displacement of the specimen recorded at the point of failure. D is the diameter of the specimen.

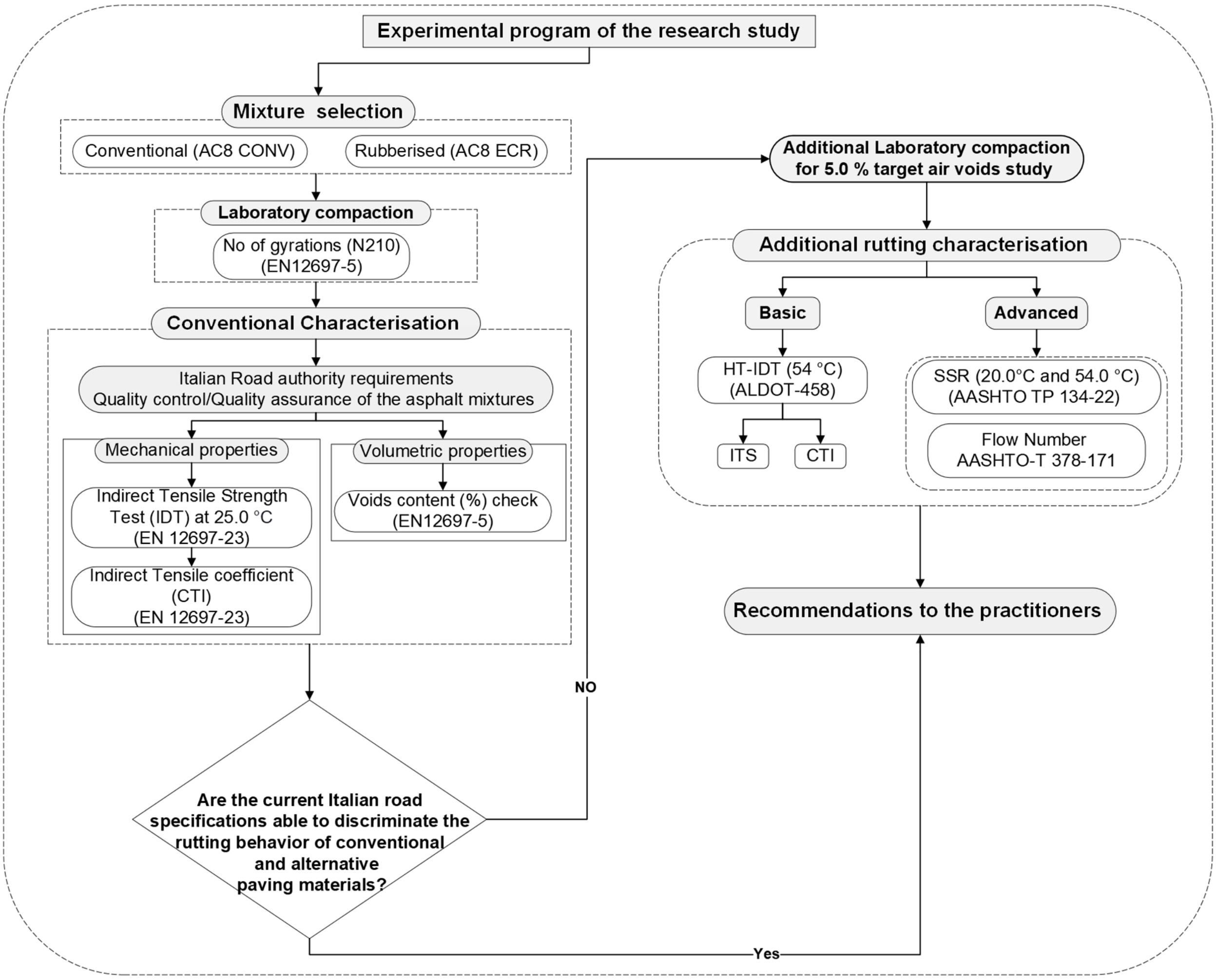

Figure 2. Schematic representation of the research study.

2.3. *Additional Rutting Characterization*

2.3.1. Basic Level

High-Temperature Indirect Tensile Strength (HT-IDT) Evaluation

Similar to IDT tests conducted at 25.0 °C, the fundamental performance-related test was executed under elevated temperatures using a high-temperature HT-IDT test at 54.0 °C [16]. The specimens were conditioned at the testing temperature, set as 10.0 °C lower than the average temperature observed over a week, taking into account the highest pavement temperature. The HT-IDT test was conducted by following the specifications of ALDOT-458. Furthermore, the benchmark values for characterizing the rutting resistance are provided in Table 3. Mixtures having an equal or greater strength than 0.44 Mpa have an excellent rutting resistance while a mixture with a strength less than 0.20 MPa is considered a poorly rutting-resistant mixture [16]. Similar to the CTI obtained at 25, the indirect tensile coefficient (CTI) of both the mixtures were calculated using the formula in Equation (2) with a temperature of 54 °C.

Table 3. Benchmark values for rutting resistance of the asphalt mixtures.

Characterization Level	Standard	Parameter	Performance	
Basic (rutting resistance)	ALDOT-458	HT-ITS (MPa)	>0.44	Excellent
			0.32 ≤ 0.44	Good
			0.20 ≤ 0.32	Fair
			≤0.20	Poor
Advanced (rutting resistance)	AASHTO T378-171	Flow number (FN)	Traffic (10^6 ESALs)	Minimum FN
			<3	-
			3 to <10	50
			10 to <30	190
			≥30	740
	AASHTO TP 134-22	Rutting strain index (RSI)	Traffic (10^6 ESALs)	RSI (%)
			<10	<12 (S)
			10 to 30	<4.0 (H)
			>30	<2.0 (V)
			≥30 slow traffic	<1.0 (E)

2.3.2. Advanced Level

Flow Number (FN) Assessment

The assessment of advanced-level performance focuses on studying rutting resistance using an AMPT following the guidelines of AASHTO TP 79-13. The FN examination was performed to check the lasting permanent deformation in asphalt compositions. The FN test was conducted under the specifications of AASHTO T 378-171. FN is a typical type of test used to evaluate permanent deformation based on pass and fail criteria. The load cycles align with the smallest rate of variation in the lasting axial strain throughout a repetitive load assessment. The FN test performed at 54.0 °C is an adapted form of the repeated-load rutting test method employed by researchers since the 1970s to gauge the rutting potential of asphalt concrete. The minimum recommended range, summarized in Table 3, for 3 to 10 million ESALs of traffic is 50. Mixtures having an FN greater than 740 have excellent rutting resistance and can be used for roadways having greater than or equal to 30 million ESALs [35,36].

Stress Sweep Rutting (SSR) Assessment

The SSR test was conducted using the AASHTO TP 134-22 standard, involving the testing of four cylindrical specimens for each mixture. In the SSR assessment, both high (T_H at 54.0 °C) and low (T_L at 20.0 °C) temperatures are taken into account. The testing temperatures were calculated by using the equation given in AASHTO TP 134-22. At each temperature setting, a vertical pressure is exerted over 600 cycles across three different deviatoric stress levels (with 200 loading increments for every segment). The sequence of the deviatoric stress levels is 483, 689, and 896 KPa for T_L, while for T_H, the sequence is 689, 483, and 896 KPa. This is because of the construction of the reference curve at 689 KPa. A pressure of 69.0 KPa is introduced using a loading pulse lasting 0.4 s, succeeded by a relaxation period of 3.6 s for T_H and 1.6 s for T_L [26,37].

Determination of Permanent Strain Using Shift Model

The outputs from the SSR tests are also used to evaluate the permanent strain using FlexMAT™ rutting. The working mechanism of this tool is based on the shift model. The shift model assesses how loading duration, temperature, and vertical force influence rutting performance. The shift model bears resemblance to the 2s2p1D model for stiffness assessments using the dynamic modulus test. The effect of temperature, vertical stress, and loading time is shifted by using the shift factors to check the rutting performance. The initial assessment is based on the first 200 cycles at a high temperature, generating a reference curve at a deviatoric stress level of 689 KPa. The outputs of the shift model also aid in the calculation of the RSI [26,38,39].

Rutting Strain Index(RSI) Quantification

The RSI measures the enduring deformation in an asphalt layer in relation to the layer's thickness at the end of the pavement's service lifecycle. This evaluation is carried out through 30 million repetitions of an 18-kip standard axle load, taking into account a standard structure [40]. The recommended range of RSIs for asphalt mixtures according to the specifications are summarized in Table 3. An RSI greater than or equal to 12 is for standard traffic having less than 3 million ESALs, while for extremely heavy traffic, the RSI should be less than 1.0 [41].

3. Results and Discussion

3.1. QA/QC Assurance—Italian Road Authority Requirements

3.1.1. Conventional Characterization

Volumetric Analysis

The air void content analysis was carried out by using the energy compaction process. According to the Italian road authority, each asphalt mixture should have a specific range of air voids depending on the design's number of gyrations in Table 2 [25]. As can be seen in Figure 3, the air void content consistently decreases in the AC8 ECR mix, especially at a higher number of gyrations, where the difference in the void content is 58%. It can be concluded that the addition of rubber particles to the mix reduces the air voids.

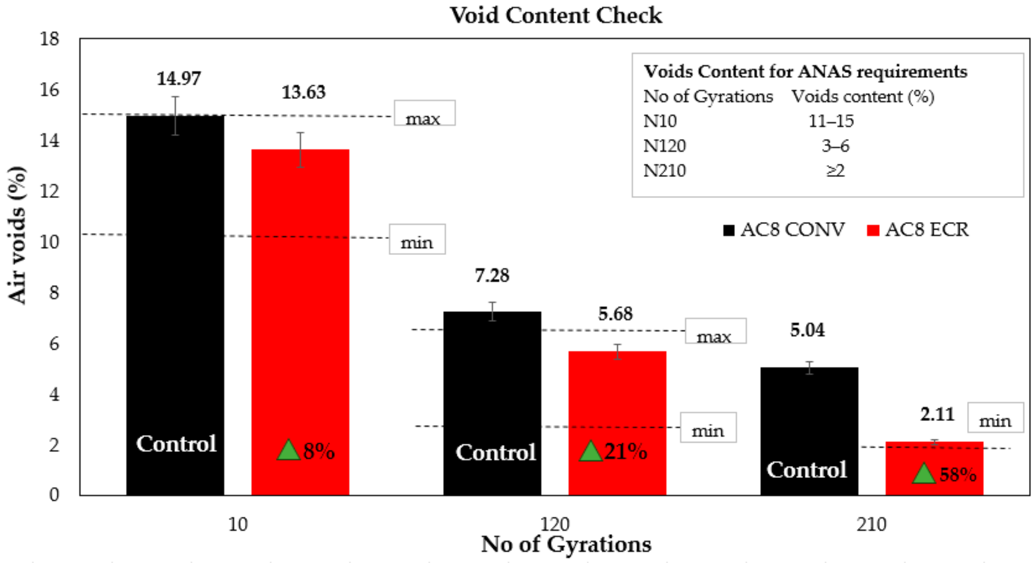

Figure 3. Void content analysis for conventional characterization.

3.1.2. Conventional IDT and CTI Analysis

The conventional IDT test analysis was carried out on conventional and rubberized asphalt mixes to check the effect of strength on the energy compaction (N210) and the targeted 5.0% air void mixtures. Notably, these mixtures, when targeting the 5.0% air voids inside both the mixtures, demonstrate an almost similar ITS value, with a percentage difference of only 1.89% and 2.33%, as shown in Figure 4. Importantly, both mixtures meet the stipulated requirements of the Italian road authority (ANAS) [25]. The minimum range for the ITS testing can be seen be in Table 2. Furthermore, if the ITS comparison is carried out between the conventional and rubberized asphalt mixes, then the difference is around 35.0%. However, it should be noted that the IDT at 25.0 °C was only measured to check its compliance with the road authorities. The further goal was to compare the laboratory compaction process based on the energy compaction and target air voids.

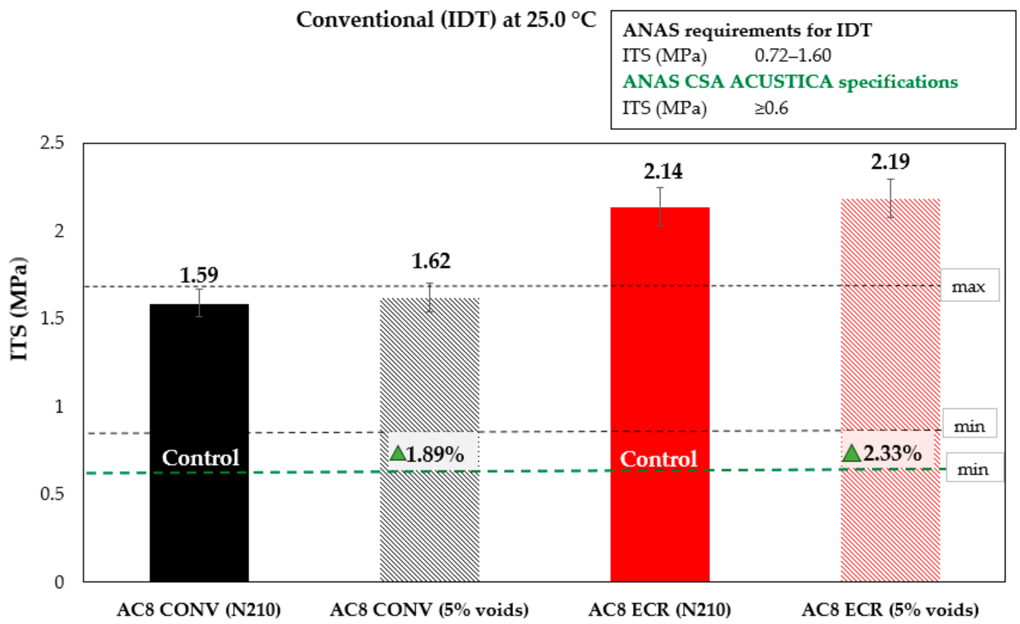

Figure 4. Indirect tensile strength analysis for conventional characterization.

The indirect tensile coefficient (CTI) for both the conventional and rubberized asphalt mixes are calculated from the IDT obtained at 25.0 °C. The minimum range recommended by the Italian road authority (ANAS) can be seen in Table 2. Figure 5 exhibits the results of both mixtures and it can be seen that the Italian road authority requirements can be fulfilled by both mixes [25]. Based on the CTI, it can be observed that there is no clear difference found between the energy compaction process (N210) and 5.0% target air voids between each mixture. However, it should noted that the difference between the conventional and rubberized asphalt mixtures based on the 5.0% target air voids is around 69.0%. However, with conventional characterization, the IDT measured at 25.0 °C does not allow us to highlight the strength advantages of the crumb rubber in asphalt mixtures in terms of the rutting behavior.

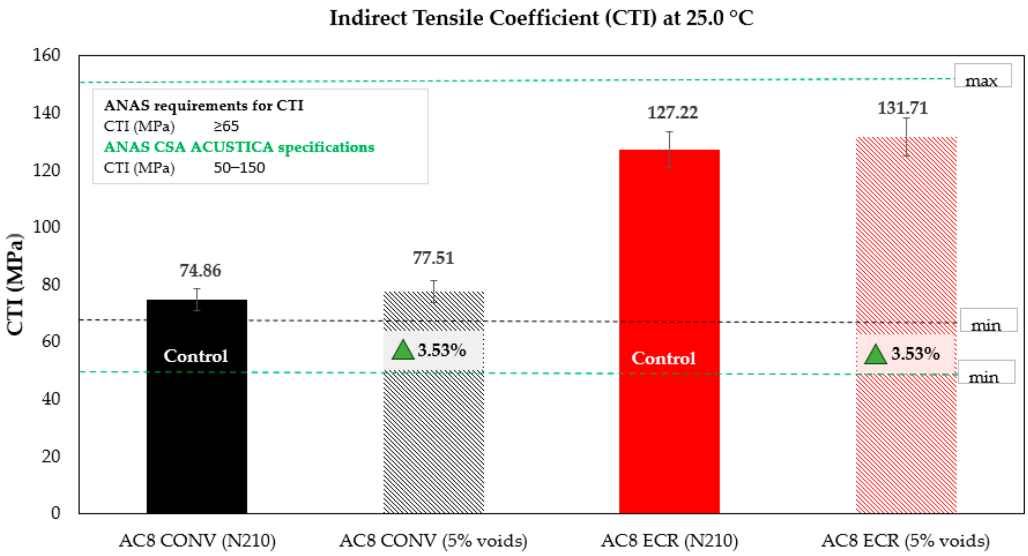

Figure 5. Indirect tensile coefficient analysis of conventional and rubberized asphalt mixes.

3.2. Summary of the Conventional Characterization

Based on Figures 4 and 5, it can be summarized that based on the ITS and CTI, both the mixtures can be investigated further for performance evaluation in terms of their rutting behavior. Therefore, the results of this research recommend target air void study instead of energy compaction for the additional rutting behavior of the conventional and rubberized asphalt mixes.

3.3. Additional Rutting Characterization

3.3.1. Basic-Level Rutting Behavior

High-Temperature (HT-IDT) and CTI Analysis

The high-temperature IDT was performed to characterize the conventional and rubberized asphalt mixes for the rutting behavior. In Figure 6, the HT-IDT results are presented, highlighting that the AC8 ECR mix stands out in terms of its average strength as compared to the conventional AC8 CONV mix. Meanwhile, AC8 CONV is categorized as having "poor" rutting resistance according to the standards summarized in Table 3, whereas AC8 ECR attains an "average" rating [42]. Based on the high-temperature indirect tensile strength test results, the addition of the rubber particles shows better resistance as compared to the conventional mix. As the conventional mix is able to bear the load of <3 million ESALs, it lies in the "poor" category described by the standard, while the rubberized mix lies in the "fair" category. Although the rubberized asphalt mix is 73.0% better in terms of resistance to permanent deformation, it still cannot be recommended for heavy traffic (>30 million ESALs). One reason for this is that at a high temperature, the rubber particles may melt inside the mixture, and subsequently, the stiffness of the mixture decreases because of the softness of the rubber particles [43,44].

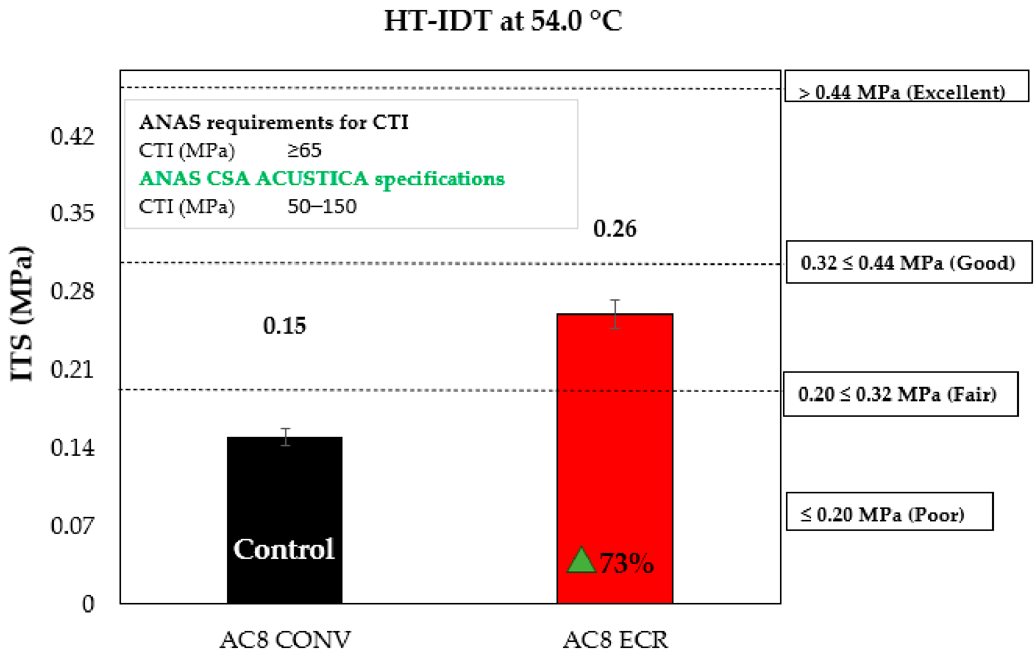

Figure 6. High-temperature indirect tensile strength analysis.

The indirect tensile coefficient (CTI) for both the conventional and rubberized asphalt mixes are calculated from the high-temperature IDT obtained at 54.0 °C. As can be seen in Figure 7, both the conventional and rubberized mixes exhibit a drastic difference in the CTI at 54.0 °C as compared to the CTI at 25.0 °C. The difference in the CTI between the conventional and rubberized asphalt mixes is around 77.65%. One reason for the minimum values of the CTI at high temperatures could be the softness of the mix. However, it is recommended that more research needs to be carried out on the CTI [43].

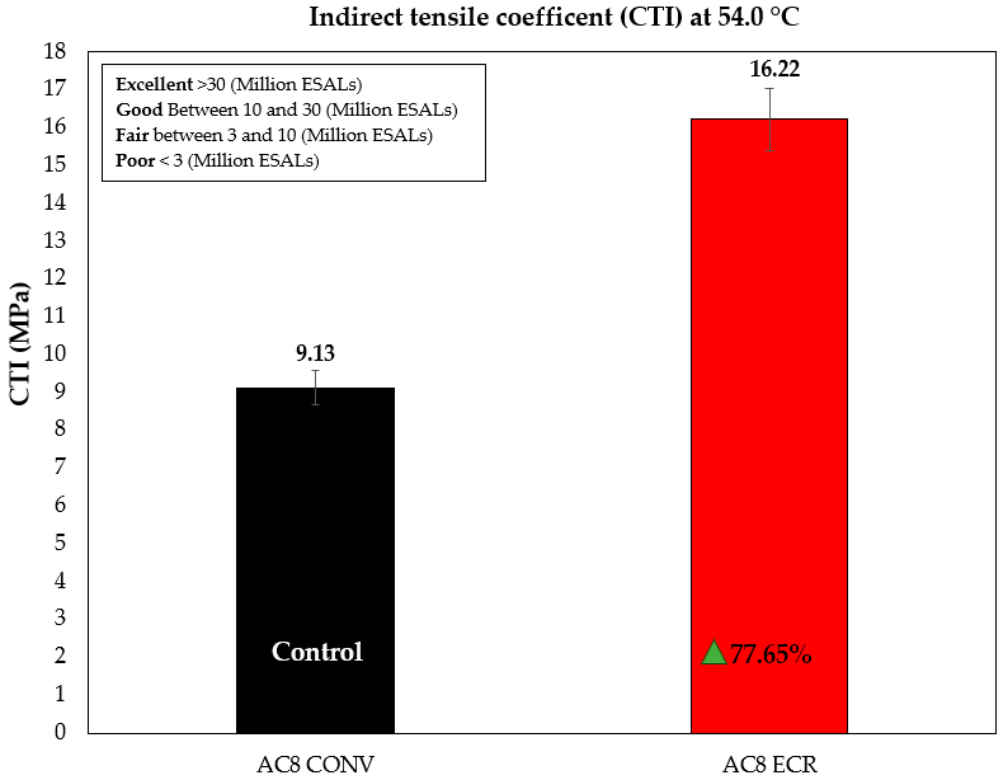

Figure 7. Indirect tensile coefficient analysis at high temperature for rutting behavior.

3.3.2. Advanced-Level Rutting Behavior

Flow Number (FN) Analysis

As illustrated in Figure 8, AC8 CONV has a higher slope and therefore a higher level of deformation is observed than that in AC8 ECR. The conventional mix deforms plastically before the rubberized mix. The linear analysis of AC8 CONV showed less resistance to permanent deformation as compared to the rubberized asphalt mix.

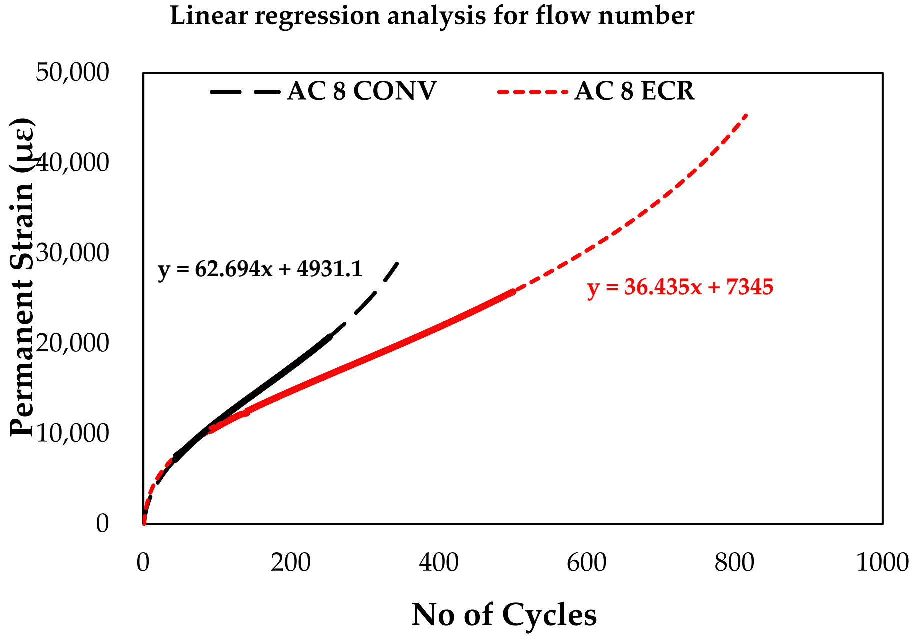

Figure 8. Linear analysis of conventional and rubberized asphalt mix for flow number.

No significant difference has been found by performing linear regression on both the conventional and rubberized asphalt mix. But the FN was calculated for AC8 CONV and AC8 ECR, as shown in Figure 9, and the minimum range recommended by the standards are summarized in Table 3. The difference in the resistance to permanent deformation between AC8 CONV and AC8 ECR was found to be 34%. Referring to Figure 9, it can be concluded that rubberized asphalt shows a significant difference in terms of the resistance to permanent deformation and is recommended for a load greater than or equal to 30 million ESALs [45,46]. Furthermore, it can also be seen that rubberized asphalt mixes are not recommended for heavy traffic because the rubberized mix is unable resist permanent deformation and would not achieve a higher flow number. At a high temperature, the rubber particles become soft and the stiffness of the mix becomes reduced, due to which, plastic flow may occur inside the rubberized mix.

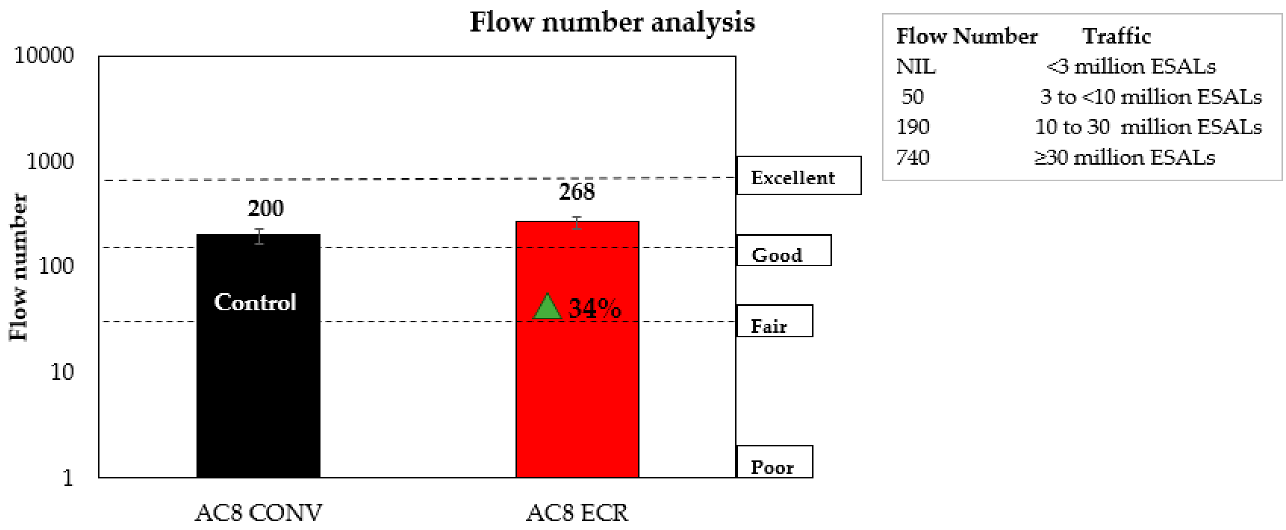

Figure 9. Flow number evaluation of conventional and rubberized asphalt mixes.

Stress Sweep Rutting Test (SSR) and RSI Results

The average permanent strain results at both 54.0 °C and 20.0 °C are shown in Figure 10a,b, along with the trend in the permanent deformation accumulation across varying cycle counts. This clearly indicates a distinct advantage for the AC8 ECR mixture. Specifically, this mixture consistently demonstrates minimal permanent strain, both at low and high temperatures, showcasing its superior resistance to rutting [1]. In comparison to the conventional AC8 CONV mix, the modified AC8 ECR proves to be significantly less susceptible to rutting, with an average percentage difference of around 9.0%. But the difference between the conventional and rubberized asphalt mix is not more than 9.0% and 24%. It can be concluded that based on permanent strain accumulation, there is not a significant difference. By taking environmental conditions, vertical stress values, and SSR outputs into account, the RSI can be calculated to further characterize these mixtures in terms of the different categories of traffic loading and layer thicknesses.

To gain a more comprehensive understanding of the permanent strain developed in conventional and rubberized asphalt mixtures, an advanced analysis was conducted, using the FlexMAT rutting tool to elaborate the calculation of the RSI [41,47]. The calculated RSI values for AC8 CONV and AC8 ECR were compared with the standard, as shown in Figure 10. For the conventional mixture AC8 CONV, the RSI value obtained was 6.53% and so it was recommended for standard traffic. The RSI for AC8 ECR is 3.89%, which means it is recommended for heavy traffic, according to the standard values shown in Figure 11. The recommended ranges for the RSI are summarized in Table 3. From the RSI calculations, it can be concluded that a lower amount of permanent strain is likely to occur in rubberized asphalt mix as compared to the conventional mix. This highlights the superior performance of AC8 ECR in terms of rutting resistance compared to conventional mixtures. But the rubberized asphalt mix is still unable to resist permanent deformation caused by heavy and extreme traffic conditions. Rubberized asphalt mix provides better resistance to permanent deformation but, likewise, in HT-IDT and FN, at high temperatures, the rubberized asphalt mix became less stiff and unable to resist permanent deformation. This may happen because of the melting of rubber particles at high temperatures.

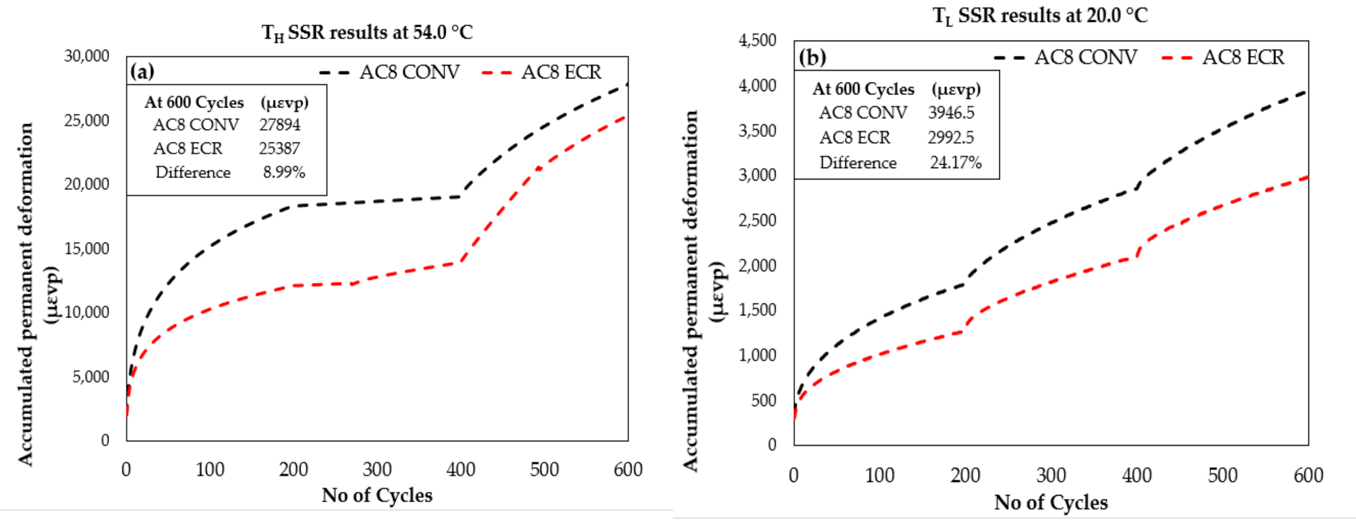

Figure 10. (**a**) Permanent strain at high temperature. (**b**) Permanent strain at low temperature.

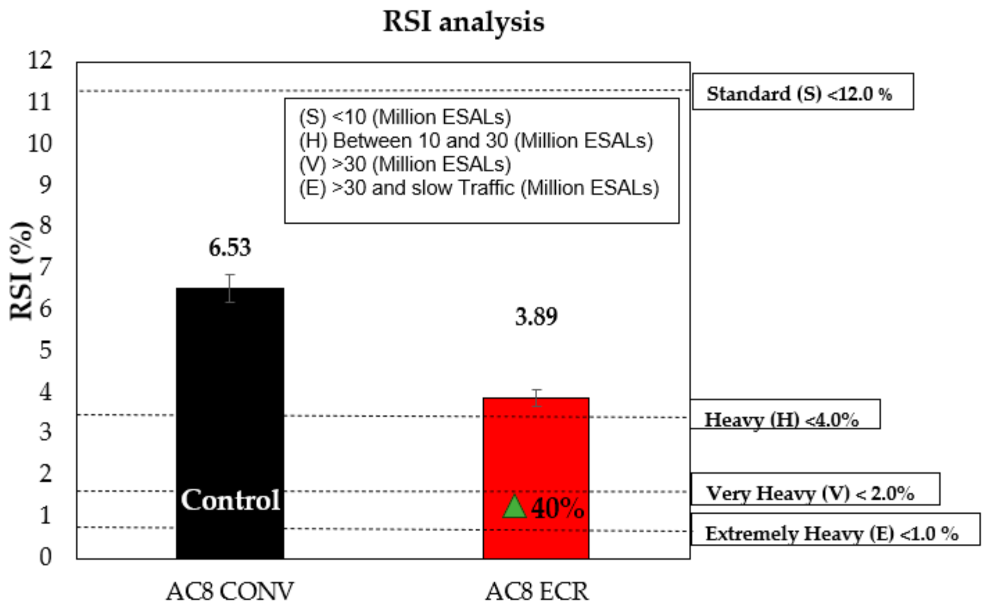

Figure 11. Rutting strain index analysis of conventional and rubberized asphalt mixes.

4. Summary of the Results

This study indicates the difference in the target air void study and energy compaction process that is used by the Italian road authorities and also highlights the incorporation of ECR in modifying the rutting behavior of conventional asphalt mixtures, specifically for wearing courses.

Volumetric properties:

- Similarities were found for both the energy compaction method for quality assurance and quality control (QA/QC) by the Italian road authorities and 5.0% target air voids. The difference observed was 1.89 and 2.33%.

Mechanical properties:

- The difference in the IDT at 25 °C for QA/QC using ITS and CTI test parameters were 35% and 70%, respectively.
- The basic-level HT-IDT at 54 °C appears to play a pivotal role in improving the material's ability to resist permanent deformation by means of additional rutting behavior (a 73.0% difference was observed), while a difference of 77% in HT-CTI was observed.
- With the rutting behavior measured using the advanced-level approach, the FN 54.0 °C showed a difference of 34%. The SSR at both low (20.0 °C) and high (54.0 °C) temperatures provided differences of 9.0% and 24.0%, respectively, at 600 cycles, and a deviatoric stress level of 896 KPa.
- The RSI analysis showed that a clear transformation from a standard traffic status to an exceptional capability to withstand heavy traffic is indicative of the pronounced benefits of incorporating ECR into conventional asphalt mixtures. The difference in the RSI (%) was 40.0% between the conventional and rubberized asphalt mixtures.

5. Conclusions and Recommendations

This research study aims at assessing the differences in predicting permanent deformation for conventional asphalt mixtures and those modified with ECR. The following conclusions have been made from the summarized results, shown in Table 4.

- In terms of the volumetrics, the following was concluded:
  - For conventional characterization, it can be concluded that the target air void study procedure as required for the performance analysis can be adopted instead of the energy compaction process.
- In terms of the mechanical properties, the following was concluded:
  - The conventional characterization for quality assurance and quality control (QA/QC) by the Italian road authorities showed a comparable difference (<35%) between the conventional and alternative paving materials (rubberized asphalt mixes) in terms of bearing capacity by means of the ITS. Instead, when looking at flexibility, by means of the CTI, the investigation always showed a huge difference (>70%) between the conventional and rubberized asphalt mixes.
  - The additional rutting behavior assessed at the basic level (by means of both HT-ITS and HT-CTI) always showed a huge difference (>70%) between the conventional and rubberized asphalt mixes.
  - A significant difference (>36% and <69%) between the conventional and alternative rubberized asphalt paving material mixes were found using the additional rutting behavior assessed at the advanced level (by means of AMPT).

Regardless of the complexity of the approach, both the basic and advanced rutting related characterizations clearly demonstrated differences in evaluating the permanent deformation between the mixtures. Thus, this research highlights that while the conventional IDT parameter, as per Italian specifications, may not exhibit a discernible impact with the addition of ECR, the addition of specific rutting-related testing through both basic- and advanced-level approaches reveals a substantial difference amongst the mixtures. It must be highlighted that the advanced-level testing offers valuable insights into the nuanced development of permanent strains over a prolonged period of 240 months, particularly under diverse climatic conditions. However, based on the results of this research, it can be concluded that both the basic- and advanced-level approaches are adoptable for rutting characterization of alternative paving materials depending upon the availability of apparatus in different research laboratories around the globe.

Table 4. Comparison of the conventional and rubberized asphalt mixtures. = (35% comparable); + (36–69% significant difference); ++ (>70% huge difference).

Trends in Characterization of Conventional and Rubberized Asphalt Mixes						
			Mixture Type			
Characterization type	Test type	Test parameter	Test temperature (°C)	AC8 CONV (Control)	AC8 ECR (Rubberized)	Trend
Conventional	IDT	ITS	25.0	1.62 MPa	2.19 MPa	35% (=)
QA/QC—Italian road authority requirements		CTI	25.0	77.51 MPa	131.71 MPa	++ 70%
Basic	HT-IDT	ITS	54.0	0.15 MPa	0.26 MPa	++ 73%
(rutting behavior)		CTI	54.0	9.13 MPa	16.22 MPa	++ 77%
Advanced	FN		54.0	200	268	= 35%
(rutting behavior)	SSR (RSI)		20.0 and 54.0	6.53%	3.89%	+ 40%

It is evident that a further obstacle to the widespread adoption of alternative paving materials is represented by specifications. This study highlights how additional performance-related testing for rutting might provide different predictions compared to testing developed for more conventional bituminous paving materials. On the basis of these conclusions, this study suggests that in order to catch the benefits of alternative paving materials and improve their widespread adoption, road authorities worldwide should adapt their QA/QC procedures towards performance-related specifications. In the case of rubberized asphalt mixtures in Italy, it is suggested to keep using an IDT-based system (ITS and CTI) complemented with the addition of any of the above rutting-related characterization methods.

Author Contributions: Conceptualization D.L.P. and F.G.; data curation, U.G. and D.L.P.; formal analysis, U.G., S.M., D.L.P. and G.G.; funding acquisition, D.L.P.; investigation, U.G., G.G. and D.L.P.; methodology, S.M., D.L.P., U.G. and G.G.; project administration, D.L.P., S.M. and U.G.; resources, S.M. and D.L.P.; writing—original draft, U.G., D.L.P. and S.M.; writing—review and editing, U.G., S.M., D.L.P. and G.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research is supported by the Italian Ministry MUR, with DM 1061 from 10 August 2021, under the financial resource of PON "Ricerca e Innovazione 2014–2020" Action IV.5 Doctorates on green themes, and is partially supported by SMACOM Srl.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All the necessary data required for supporting this research are included in this paper.

Acknowledgments: The authors would like to acknowledge Ecopneus scpa for the support provided through the project RUBBERAP and RubLab Srl and SicilBitumi Srl for their interest and support in kind.

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

References

1. Meroni, F.; Flintsch, G.W.; Habbouche, J.; Diefenderfer, B.K.; Giustozzi, F. Three-level performance evaluation of high RAP asphalt surface mixes. *Constr. Build. Mater.* **2021**, *309*, 125164. [CrossRef]
2. Islam, R.; Hossain, M.I.; Tarefder, R.A. A study of asphalt aging using Indirect Tensile Strength test. *Constr. Build. Mater.* **2015**, *95*, 218–223. [CrossRef]
3. Du, Y.; Chen, J.; Han, Z.; Liu, W. A review on solutions for improving rutting resistance of asphalt pavement and test methods. *Constr. Build. Mater.* **2018**, *168*, 893–905. [CrossRef]
4. Liao, H.; Tavassoti, P.; Sharma, A.; Baaj, H. Evaluation of rutting resistance and moisture susceptibility of high RAP content asphalt mixtures containing bio-based rejuvenators. *Constr. Build. Mater.* **2023**, *401*, 132859. [CrossRef]
5. Xu, T.; Huang, X. Investigation into causes of in-place rutting in asphalt pavement. *Constr. Build. Mater.* **2012**, *28*, 525–530. [CrossRef]
6. Chilukwa, N.; Lungu, R. Determination of layers responsible for rutting failure in a pavement structure. *Infrastructures* **2019**, *4*, 29. [CrossRef]
7. Ghani, U.; Zamin, B.; Bashir, M.T.; Ahmad, M.; Sabri, M.M.S.; Keawsawasvong, S. Comprehensive study on the performance of waste HDPE and LDPE modified asphalt binders for construction of asphalt pavements application. *Polymers* **2022**, *14*, 3673. [CrossRef] [PubMed]
8. Simpson, A.L.; Daleiden, J.F.; Hadley, W.O. Rutting analysis from a different perspective. *Transp. Res. Rec.* **1995**, *1473*, 9.
9. Fwa, T.F.; Tan, S.A.; Zhu, L.Y. Rutting prediction of asphalt pavement layer using C-ϕ model. *J. Transp. Eng.* **2004**, *130*, 675–683. [CrossRef]
10. Boz, I.; Habbouche, J.; Diefenderfer, S.D.; Coffey, G.; Seitllari, A.; Ozbulut, O.E. Evaluating the Rutting Potential of Asphalt Mixtures with Simple and Practical Tests. *Transp. Res. Rec. J. Transp. Res. Board* **2023**, 03611981231207089. [CrossRef]
11. Hong, F.; Chen, D. Evaluation of asphalt overlay permanent deformation based on ground-penetrating radar technology. *J. Test. Evaluation* **2016**, *44*, 1716–1723. [CrossRef]
12. Fontes, L.P.; Trichês, G.; Pais, J.C.; Pereira, P.A. Evaluating permanent deformation in asphalt rubber mixtures. *Constr. Build. Mater.* **2010**, *24*, 1193–1200. [CrossRef]
13. Zaumanis, M.; Poulikakos, L.; Partl, M. Performance-based design of asphalt mixtures and review of key parameters. *Mater. Des.* **2018**, *141*, 185–201. [CrossRef]

14. Yazdipanah, F.; Ameri, M.; Shahri, M.; Hasheminejad, N.; Haghshenas, H.F. Laboratory investigation and statistical analysis of the rutting and fatigue resistance of asphalt mixtures containing crumb-rubber and wax-based warm mix asphalt additive. *Constr. Build. Mater.* **2021**, *309*, 125165. [CrossRef]
15. Chaturabong, P.; Bahia, H.U. Mechanisms of asphalt mixture rutting in the dry Hamburg Wheel Tracking test and the potential to be alternative test in measuring rutting resistance. *Constr. Build. Mater.* **2017**, *146*, 175–182. [CrossRef]
16. Vamsikrishna, G.; Singh, D. Comparison of Rutting Resistance of Plant Produced Asphalt Mixes Using Hamburg Wheel Tracker and Surrogate Simple Performance Tests: IDEAL-RT and HT-IDT. *J. Mater. Civ. Eng.* **2023**, *35*, 04023471. [CrossRef]
17. Wang, D.; Baliello, A.; Pinheiro, G.d.S.; Poulikakos, L.D.; Tušar, M.; Vasconcelos, K.L.; Kakar, M.R.; Porot, L.; Pasquini, E.; Giancontieri, G.; et al. Rheological Behaviors of Waste Polyethylene Modified Asphalt Binder: Statistical Analysis of Interlaboratory Testing Results. *J. Test. Eval.* **2023**, *51*, 2199–2209. [CrossRef]
18. Tušar, M.; Kakar, M.R.; Poulikakos, L.D.; Pasquini, E.; Baliello, A.; Pasetto, M.; Porot, L.; Wang, D.; Falchetto, A.C.; Dalmazzo, D.; et al. RILEM TC 279 WMR round robin study on waste polyethylene modified bituminous binders: Advantages and challenges. *Road Mater. Pavement Des.* **2023**, *24*, 311–339. [CrossRef]
19. Li, H.; Jiang, H.; Zhang, W.; Liu, P.; Wang, S.; Wang, F.; Zhang, J.; Yao, Z. Laboratory and field investigation of the feasibility of crumb rubber waste application to improve the flexibility of anti-rutting performance of asphalt pavement. *Materials* **2018**, *11*, 1738. [CrossRef]
20. Picado-Santos, L.G.; Capitão, S.D.; Neves, J.M. Crumb rubber asphalt mixtures: A literature review. *Constr. Build. Mater.* **2020**, *247*, 118577. [CrossRef]
21. Giancontieri, G.; Hargreaves, D.; Presti, D.L. Are we correctly measuring the rotational viscosity of heterogeneous bituminous binders? *Road Mater. Pavement Des.* **2020**, *21* (Suppl. 1), S37–S56. [CrossRef]
22. Medina, J.G.; Giancontieri, G.; Presti, D.L. Quality control of manufacturing and hot storage of crumb rubber modified binders. *Constr. Build. Mater.* **2020**, *233*, 117351. [CrossRef]
23. Giancontieri, G.; Hargreaves, D.; Partal, P.; Presti, D.L. Unlocking the Dual Helical Ribbon for rotational viscosity measurements of highly heterogeneous fluids. *Mater. Des.* **2024**, *241*, 112920. [CrossRef]
24. Lo Presti, D. Recycled Tyre Rubber Modified Bitumens for road asphalt mixtures: A literature review. *Constr. Build. Mater.* **2013**, *49*, 863–881. [CrossRef]
25. SpA, A. Capitolato Speciale D'Appalto-Norme Tecniche per l'esecuzione del Contratto Parte 2. Coordinamento Territoriale/Direzione IT. PRL. 2016. Available online: https://www.stradeanas.it/sites/default/files/CSA%20NT%207IMSS2019%20%20Budduso'.pdf (accessed on 30 May 2024).
26. Kim, D.; Kim, Y.R. Development of Stress Sweep Rutting (SSR) test for permanent deformation characterization of asphalt mixture. *Constr. Build. Mater.* **2017**, *154*, 373–383. [CrossRef]
27. Ziari, H.; Divandari, H.; Hajiloo, M.; Amini, A. Investigating the effect of amorphous carbon powder on the moisture sensitivity, fatigue performance and rutting resistance of rubberized asphalt concrete mixtures. *Constr. Build. Mater.* **2019**, *217*, 62–72. [CrossRef]
28. Raschia, S.; Tattolo, S.; Rilievi, A. Evaluation of high percentage of alternative aggregates for the production of hot mix asphalt surface layers. *Road Mater. Pavement Des.* **2023**, *25*, 56–71. [CrossRef]
29. Ghani, U.; Milazzo, S.; Giancontieri, G.; Mignini, C.; Buttitta, G.; Gu, F.; Presti, D.L. Unveiling the Benefits of Engineered Crumb Rubber for Asphalt Mixtures via Performance-Related Characterization: Rutting Behavior. *Eng. Proc.* **2023**, *36*, 39. [CrossRef]
30. Mallick, R.B. Use of Superpave gyratory compactor to characterize hot-mix asphalt. *Transp. Res. Rec. J. Transp. Res. Board* **1999**, *1681*, 86–96. [CrossRef]
31. ANAS. I quaderni tecnici per la salvaguardia delle infrastrutture. *Quad. Tec.* **2019**, *17*, 76.
32. Scotton, R. Il Riciclaggio a Freddo Nelle Pavimentazioni Stradali: Caratterizzazione Prestazionale di Diverse Miscele in Conglomerato Bituminoso Schiumato. 2013. Available online: https://www.politesi.polimi.it/handle/10589/97761 (accessed on 30 May 2024).
33. Jeong, J.; Underwood, B.S.; Kim, Y.R. Rutting performance prediction using index-volumetrics relationships with stress sweep rutting test and Hamburg wheel-track test. *Constr. Build. Mater.* **2021**, *295*, 123664. [CrossRef]
34. Zhang, Y.; Ma, T.; Ding, X.; Chen, T.; Huang, X.; Xu, G. Impacts of air-void structures on the rutting tests of asphalt concrete based on discretized emulation. *Constr. Build. Mater.* **2018**, *166*, 334–344. [CrossRef]
35. Alavi, A.H.; Ameri, M.; Gandomi, A.H.; Mirzahosseini, M.R. Formulation of flow number of asphalt mixes using a hybrid computational method. *Constr. Build. Mater.* **2011**, *25*, 1338–1355. [CrossRef]
36. Wang, H.; Zhan, S.; Liu, G.; Xiang, J. The effects of asphalt migration on the flow number of asphalt mixture. *Constr. Build. Mater.* **2019**, *226*, 442–448. [CrossRef]
37. Ghanbari, A. *Stress Sweep Rutting (SSR) Test: AMPT*; North Carolina State University: Raleigh, NC, USA, 2018.
38. Wang, Y.D.; Ghanbari, A.; Underwood, B.S.; Kim, Y.R. Development of preliminary transfer functions for performance predictions in FlexPAVE™. *Constr. Build. Mater.* **2021**, *266*, 121182. [CrossRef]
39. Joumblat, R.; Masri, Z.A.B.A.; Al Khateeb, G.; Elkordi, A.; El Tallis, A.R.; Absi, J. State-of-the-art review on permanent deformation characterization of asphalt concrete pavements. *Sustainability* **2023**, *15*, 1166. [CrossRef]
40. Lee, J.-S.; Lee, S.-Y.; Le, T.H.M. Developing performance-based mix design framework using asphalt mixture performance tester and mechanistic models. *Polymers* **2023**, *15*, 1692. [CrossRef] [PubMed]

41. Kim, Y.R.; Ghanbari, A.; Underwood, S. *Rutting Strain Index (RSI) Parameter for Asphalt Performance Engineered Mixture Design [Tech Brief]*; Federal Highway Administration. Office of Research, Development, and Technology: Washington, DC, USA, 2021.
42. Christensen, D.W.; Bonaquist, R.; Anderson, D.A.; Gokhale, S. Indirect tension strength as a simple performance test. *Transp. Res. Circ. Number E-C068* **2004**, 44–57.
43. Nguyen, H.T.; Tran, T.N. Effects of crumb rubber content and curing time on the properties of asphalt concrete and stone mastic asphalt using dry process. *Int. J. Pavement Res. Technol.* **2018**, *11*, 236–244. [CrossRef]
44. Bennert, T.; Haas, E.; Wass, E. Indirect Tensile Test (IDT) to determine asphalt mixture performance indicators during quality control testing in New Jersey. *Transp. Res. Rec. J. Transp. Res. Board* **2018**, *2672*, 394–403. [CrossRef]
45. Yu, H.; Shen, S. *An Investigation of Dynamic Modulus and Flow Number Properties of Asphalt Mixtures in Washington State*; Report No. TNW; Transportation Northwest (TransNow) UTC: Seattle, WA, USA, 2012.
46. Shirini, B.; Imaninasab, R. Performance evaluation of rubberized and SBS modified porous asphalt mixtures. *Constr. Build. Mater.* **2016**, *107*, 165–171. [CrossRef]
47. Ghanbari, A.; Underwood, B.S.; Kim, Y.R. Development of a rutting index parameter based on the stress sweep rutting test and permanent deformation shift model. *Int. J. Pavement Eng.* **2022**, *23*, 387–399. [CrossRef]