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Article

Development of Functional Rubber-Based Impact-Absorbing Pavements for Cyclist and Pedestrian Injury Reduction

Christina Makoundou [1,*], Cesare Sangiorgi [1], Kenth Johansson [2] and Viveca Wallqvist [2]

[1] Department of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, 40131 Bologna, Italy; cesare.sangiorgi4@unibo.it
[2] Department of Material and Surface Design, Research Institutes of Sweden (RISE), 114 28 Stockholm, Sweden; kenth.johansson@ri.se (K.J.); viveca.wallqvist@ri.se (V.W.)
* Correspondence: ngongo.makoundou2@unibo.it; Tel.: +39-05-1209-0215

Abstract: Cyclists, pedestrians and elderly people's specific needs in urban road infrastructures are often neglected. They rarely benefit from safety measures or innovations. Inspired by playgrounds and aiming to reduce vulnerable road users (VRUs) injuries, the development of the rubber-based impact-absorbing pavements (IAP) offers a possibility to rethink the design of urban pavements and address safety on roads, which constitutes a major challenge in terms of attaining more sustainable, resilient, and safe cities. Therefore, bituminous mixtures with four different crumb rubber contents, 0%, 14%, 28%, and 33% (in total weight), were produced by partial aggregates substitution using the dry process. After the assessment of the geometrical and volumetric properties, the mechanical performances were evaluated. Finally, the samples were tested to measure the abrasion and impact attenuation with the well-known head injury criterion (HIC), at different temperatures from −10 to 40 °C, to obtain a wide range of values referring to possible weather conditions. A significant effect of the rubber percentage and layer thickness on impact attenuation was observed. All observations and results confirm the feasibility of the IAP concept and its positive effect on future injury-prevention applications.

Keywords: end-of-life tyres; crumb rubber; impact-absorbing pavements (IAPs); pavement surfacing; bituminous mixtures; vulnerable road users (VRUs); critical fall height (CFH); head injury criterion (HIC)

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1. Introduction

1.1. Vulnerable Road Users' Safety and Public Health

Road traffic injuries result in an alarming and non-negligible amount of death in the world. More than half of deaths occur among people classified as vulnerable road users (VRUs), including pedestrians and cyclists [1,2]. Several previous studies have shown that stiff surfaces are one of the main reasons for vulnerable users traffic injuries. To protect these users, research on innovative and sustainable impact-absorbing pavements (IAP) surface layers has now become crucial [3,4].

Moreover, because roads are an essential part of the human living environment and the urban population is increasing, VRU's are increasingly subject to fall accidents impacting mostly heads, shoulders and hips [1,2]. In 2021, the World Health Organization specified that a critical number of people (between 20 and 50 million) are forced to live with disabilities resulting from non-fatal-injuries caused by the design of roads, which is often unsafe and inadequate for pedestrians, cyclists or motorcyclists [1].

In addition to the injuries and disabilities resulting from road traffic accidents, the safety of roads also influences other public health issues. Indeed, urban roads that do not include safe walking and cycling infrastructures can result in more reliance on car transportation. In these cases, people are less likely to walk or cycle, leading to other health problems that are related to sedentary lifestyle such as, for instance, ischaemic heart disease and even obesity [1]. The fear of falling, especially for the elderly, can also be observed and cause social isolation or even anxiety. All these points are assembled in the European Sustainable Development Goal (SDG) 3, which aims to ensure healthy lives and promote well-being for all ages. In particular, target 3.6 aims to considerably decrease the death rates caused by road traffic accidents and related injuries [5].

1.2. Recycling and Responsible Consumption for Sustainable Urban Communities

While designing new solutions, an environmental and sustainable perspective must be included in the technical performance requirements. Undeniably, using recycled materials instead of non-renewable resources is an effective method. The pavement industry represents one of the open improvement sectors where the use of recycled tyre rubber, in different shapes, offers a means to increase the life cycle of the overly engineered tyres, reduce CO_2 emissions, reduce the use of raw virgin mineral materials, and improve citizens' quality of life [6]. Numerous SDGs are associated with this approach to encourage cities to become more resilient and sustainable. The responsible consumption of already existing materials also impacts the protection of lands and reduces ecosystem degradation. The climate can also be indirectly preserved. Therefore, along with SDG 3, SDGs 11, 12, 13 and 15 are also linked directly or indirectly to the research on the development of IAPs [5].

For pavement materials, the stiffness modulus is a crucial value in the analysis of the stress–strain response behaviour under a traffic load [7]. The traditional flexible pavements need high stiffness that allows heavy vehicles to apply a load without large deformation. Contrary to the currently used road materials, a low-stiffness elastic pavement can withstand a larger deformations and spring back to the original dimensions. The deformation of the material makes possible the absorption of the impact forces. This is the reason why cars' external materials can deform to absorb the energy created by the impact of an accident. Therefore, a low stiffness pavement is considered a valid development to reduce the risk of injuries in case of a fall onto the pavement, thanks to the elastic properties of the recycled crumb rubber, which have been exploited for many years to enhance the flexibility and elasticity of road pavements. This material can be used as a carrier of the required stiffness. In fact, the incorporation of crumb rubber (CR), itself a low-stiffness material, in substantial quantities can decrease the stiffness of traditional pavement surfaces while contributing to their durability (less cracks) and the waste management of end-of-life tyres (ELTs) [8,9]. Therefore, the main objective of this research is to design an innovative surface layer by using CR from ELTs, allowing the reuse of waste materials in parallel with reducing the risk of injuries for fallen VRUs in the urban environment [3,4].

1.3. Inspirations and Previous Studies

The present research was inspired by playground paving materials that are used to reduce children's injuries in parks and are often partly made of recycled rubber. To rethink them for applications in urban pavements is the main challenge in terms of developing impact-absorbing pavements [3,4]. The proposed innovative paving material should be able to abate the risks of injuries for VRUs in all weather conditions and, at the same time, be durable and friendly to the environment, including the absence of emissions, fumes, or odours, without chemical leaching and particle release. Furthermore, the developed material should be produced and laid using existing technologies, and it should withstand occasional slow and heavy traffic during maintenance. Two major studies have recently been conducted on cement concrete and asphalt concrete mixes containing high rubber contents to develop shock-absorbing properties for pavements [3,4,10]. The main application for those low stiffness pavement layers is limited to sidewalks and bike lanes. According to these studies, while mentioning IAPs, the comfort and appearance (survey-based), the stiffness (compressive strength and elastic compressive modulus), the friction or ice-affinity properties (friction tester), and impact-attenuation capabilities (according to falling speed, height, area of impact, and severity, as measured via the head injury criterion (HIC) [11] are the main criteria to be adopted for the materials' characterisation [2].

Another study on rubberised shock-absorbing concrete [10] showed that it is possible to produce rubber-modified (from 59 to 77% rubber volume) concretes with sufficient load-bearing capacity for cyclists and pedestrians. The results were based on the compressive strength and elastic modulus inputs of the succession of produced samples (up to 7 MPa). These values were compared to the pressure applied by an 80 kg human walking on the material with flat-heeled shoes. The tested materials resisted the deformation applied by this pressure. However, constraints were raised about the unknown behaviour of those materials over time, as well as adverse weather conditions.

Previous studies on concrete and asphalt concretes [3,4] have demonstrated the effectiveness of high-rubber-content material on the significant decrease in HIC values. The feasibility of laying a 63% (volume) rubber content material was also proven. In Sweden, laboratory results were confirmed by field trials at the AstaZero testing facility [4]. This in situ experiment was conducted to collect information on the behaviour of the material in outdoor conditions and to evaluate the users' comfort and riding impressions regarding the experimental materials.

At present, the preliminary studies on high-content rubber materials to reach valuable shock-absorbing properties are considered as the starting point of the ongoing research. Considerable assessment efforts are necessary in relation to the durability of the proposed materials. Furthermore, the impact-absorbing properties must be consistent over time and in different weather conditions [3].

1.4. Implementation of the Current Study

As previously mentioned, this research focuses on bituminous mixes for flexible pavements with shock-absorbing properties. It should be used as alternative pavement for footpaths and bike lanes, improving the life cycle of tyres while reducing VRUs' injuries through durable, softer, safer and recycled material.

Tyre rubber is being used successfully as the primary component in terms of volume on playground materials. However, the mixing, production and construction methods are significantly different from those of bituminous asphalt paving (for example, handwork and non-bituminous binders). The challenge with this material is to ensure that it is produced and laid following the same methods as those already used in the asphalt industry. In this industry, when it comes to rubberized asphalt, the amount of rubber in the mix is limited and never reaches values comparable to those of playgrounds.

With this study, the objective is to introduce a new manner of producing impact-absorbing pavements. The aim is to implement and deploy this solution on urban roads and lay several meters with better conditions for the workers. By using known methods and existing machinery and facilities, the development of such material can have a better future, for instance, in terms of costs. Different formulations with distinct quantities of recycled rubber and binders have been produced and tested. The selected starting mixture is based on a typical Hot Rolled Asphalt (HRA), also known for containing a relatively large quantity of fine aggregates compared to other standard dense mixes. The mix design goal is to substitute a volume of natural fines with a graded quantity of CR (0–4 mm). The supplied CR was preliminarily analysed, focusing on the possible release of chemicals, using the most suitable types of PAH (Polycyclic Aromatic Hydrocarbon) analysis [12].

Traditional bituminous mixture characterisation has been performed at different temperatures, including the Indirect Tensile Stiffness Modulus test [13], the Indirect Tensile Strength test [14] and the Cantabro loss test [15]. The tests aimed to quantify the stiffness and the abrasion resistance properties of the different asphalt materials. Furthermore, due to the significant amount of rubber inside the mixtures, the specimens were also tested to comply with the playgrounds' or artificial tracks' testing methods, i.e. the HICs and the CFHs were also measured.

Those preliminary tests were meant to optimise the material in terms of the use of recycled materials, their stiffness and strength, their layer durability and the impact-attenuation performance of the IAP.

2. Materials and Methods

2.1. End-of-Life Tyre Rubber

The waste management of the ELTs and the CR production were undertaken in Sweden. These CR were used for the experimental production of IAP samples. They were produced using the ambient shredding process and were classified into three different size distributions ranging from 0 mm to 4 mm, as illustrated in Figure 1.

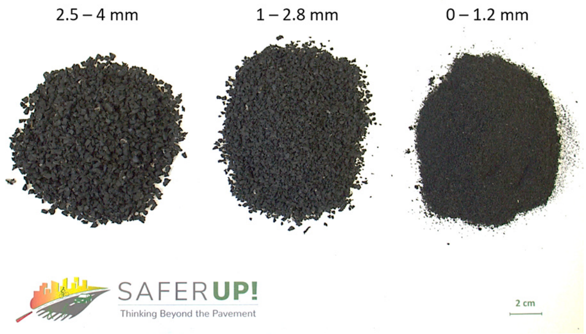

Figure 1. CR: Coarse (C), Medium (M) and Fine (F) particles used in the experimental mixtures.

Several tests were performed to measure the main characteristics of the rubber samples (Table 1). The parameter linked to the chemical characteristics and exposure risks for the workers and daily users of products containing rubber granules (e.g., playgrounds, road pavements, artificial turfs and suchlike) was also measured. One of the most significant values was that representing the presence of eight Polycyclic Aromatic Hydrocarbons (PAHs 8), which were limited to a total concentration of 20 mg/kg (0.002 % by weight) by the European Chemicals Agency [12,16,17].

Table 1. Typical properties of the experimental crumb rubber.

Crumb Rubber (CR) Granulates	Particle Size (mm)	Bulk Density [1] (kg·m^3) EN 1097-3	Specific Gravity [2] EN 1097-6	PAHs 8 REACH [1] (mg/kg) (Specification $\leq$ 20)
Fine (F)	0–1.2	0.440	1.028	6.5
Medium (M)	1–2.8	0.440	1.028	6.5
Coarse (C)	2.5–4	0.440	1.028	6.5

[1] Value given by the supplier. [2] Measured values.

In addition to the values of PAHs 8 given by the supplier, a complete analysis of 16 PAHs was performed. PAHs represent a class of organic compounds that can cause severe health issues if not under control. Eight of them are usually subject to limitations (PAHs 8). At the same time, it is strongly recommended by the European legislations to analyse the group of sixteen (PAHs 16) for their potential health and ecological influence by skin contact, inhalation or ingestion through food, for instance [12,16,18]. The lower the amounts of detected PAHs, the better the tested materials are in terms of risks for the health and the environment. The objective of the limitation is to ensure that the cancer risk from PAH exposure remains at a low level for the users who are in contact with the rubber granules. That includes workers installing and maintaining the rubberised surfaces, players using the pitches or playgrounds [12,17], or the potential VRU of the developed IAP.

Determination of the PAH content was made following the AfPS GS 2014:01 PAK standards [16]. The results and limits are presented in Table 2.

Table 2. Results from the PAH analysis.

PAH 16	Concentration Detected (mg/kg)	Sum of PAH Detected (mg/kg)
TOTAL PAH 16		Sum 16 PAH Approx.2.3
Naphthalene Acenaphthylene Acenaphthene	<0.5 <0.5 <0.5	Sum PAH-L <1.5
Fluorene Phenanthrene Anthracene Fluoranthene Pyrene	<0.5 <0.5 <0.5 <0.5 1.0	Sum PAH-M Approx. 1.0
Benzo a anthracene Chrysene Benzo b,j fluoranthene Benzo k fluoranthene Benzo a pyrene Indeno123cdpyrene Dibenzo ah anthracene Benzo ghi perylene	<0.5 <0.5 1.3 <0.5 <5 <5 <5 <5	Sum PAH-H Approx.1.3

2.2. Bituminous Binder

The binder used in this study was a 25/55 Styrene-Butadiene-Styrene (SBS) modified bitumen (PmB 1) specifically designed for the incorporation of rubber into the bituminous binder at lower production temperatures (i.e., 160 °C). The density of the binder was 1.050 g/cm^3. The typical binder parameters values are shown in Table 3.

Table 3. Characteristics of 25/55 Polymer-Modified Bitumen.

Measured Properties [1]	Unit	Value	Standard
Penetration @25 °C	0.1 mm	25/55	EN 1426
Softening point	°C	≥70	EN 1427
Flashpoint	°C	≥250	EN 2592
Dynamic viscosity @160 °C	Pa·s	≥0.4	EN 13702-1
Fraass breaking point	°C	≤−15	EN 12593

[1] Values from the binder supplier.

2.3. Virgin Aggregates

Limestones, basalt, mixed sand and a commercial limestone filler were used as natural lithic skeletons and additives for the asphalt mixture. The aggregates came from different Italian suppliers and their characteristic values are shown in Table 4.

Table 4. Properties of the virgin aggregates.

Virgin Aggregates [1]	Particle Size (mm) EN 933-1	Specific Gravity EN 1097-6
Limestone 1	8–14	2.661
Limestone 2	4–8	2.669
Sand	0–4	2.608
Basalt	0–2	2.685
Limestone filler	≤0.063	2.667

[1] Measured values.

The entire experimental plan is represented in Figure 2. The work was divided into three main sections: the mix design, the production of specimens and the compacted materials' characterisation.

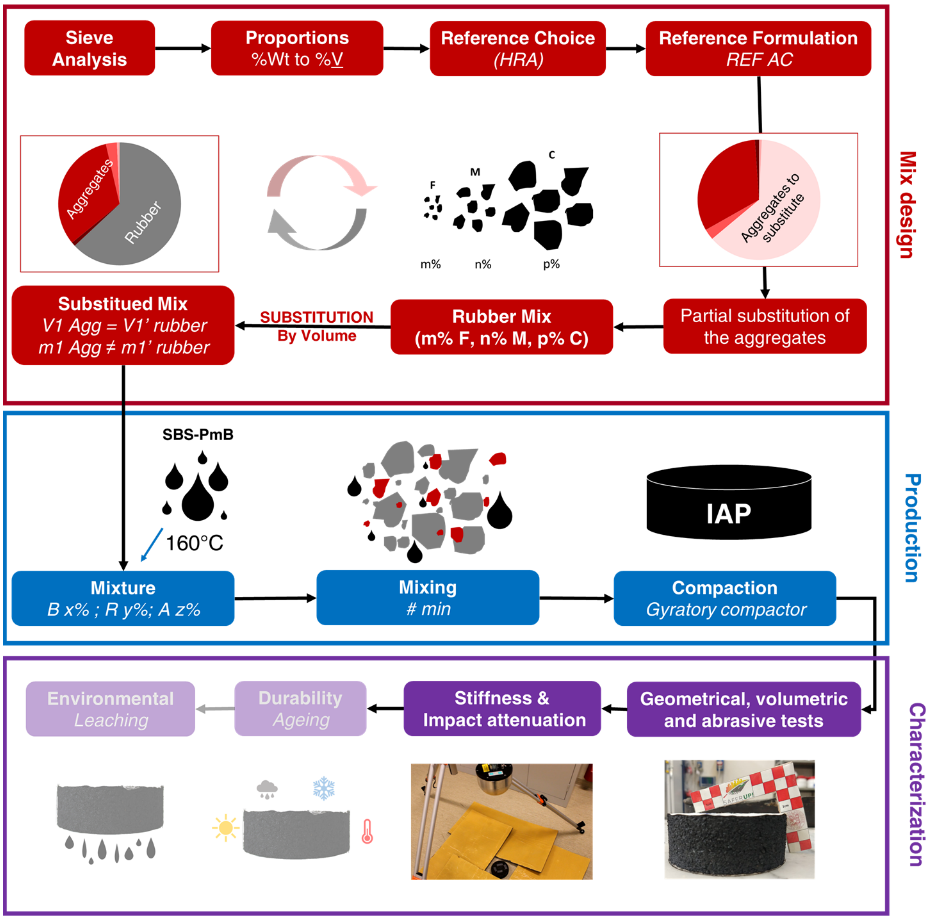

Figure 2. Scheme of the experimental investigations' approach.

2.4. Mix Design and Production of Specimens

The chosen reference mix is a Hot Rolled Asphalt (HRA). It is a dense material containing a considerable amount of sand and other fine materials. The mix design process and its proposed formulations were designed using the weight and the volume units to calibrate the substitution of sands with large amounts of rubber in the mixtures. Firstly, the rubber bulk density (given by the supplier) was used for the initial mix proportions to obtain an estimated volume fraction [4]. All experimental values are reported in Table 5.

Table 5. Content of each mix by weight and by volume based on the aggregate and the total mix.

Mixtures		% Weight			% Volume		
Name	Rubber Size	% Rubber (Aggregates)	% Rubber (Total Mix)	% Binder (Total Mix)	% Rubber (Aggregates)	% Rubber (Total Mix)	% Binder (Total Mix)
REF AC	/	0	0	8	0	0	8
IAP 1	FM	17	14	18	35	30	14
IAP 2a	FM	34	28	18	63	52	16
IAP 2b	FM	34	27	21	63	51	19
IAP 2c	FM	34	27	23	63	50	21
IAP 3	FMC	41	33	18	66	56	15

The production of samples required mixing the aggregates with bitumen (160 °C) before adding the rubber. All constituents were mixed into a homogeneous binder coating before being compacted using a standard gyratory compactor. The compaction was performed using an internal angle of 1.250°, an applied pressure of 600.000 KPa, and a speed of 30.000 Rpm, and by applying 80 cycles (Figure 3).

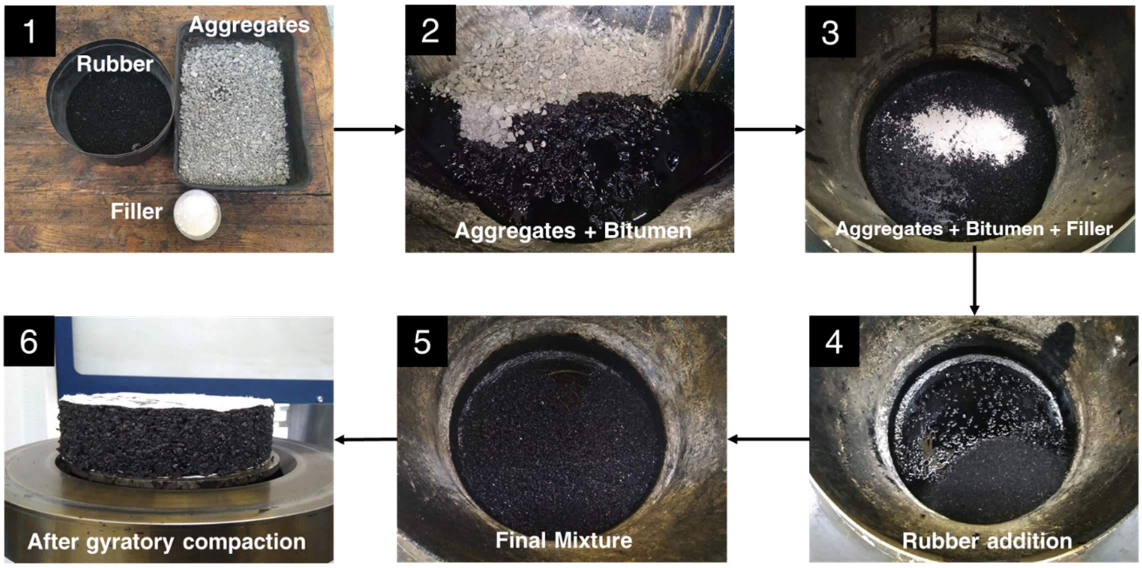

Figure 3. Production steps for the rubberised Impact-Absorbing Pavement (IAP) samples.

Firstly, IAP samples with fixed amounts of rubber (IAP 2a, IAP 2b and IAP 2c) were produced to identify the quantity of binder needed to prevent the loss of particles. Afterwards, samples with a fixed amount of bitumen were produced with four different amounts of rubber (REF, IAP 1, IAP 2a, IAP 3). All mixtures' proportions are detailed in Table 5.

2.5. Characterisation

A procedure was developed, using standard asphalt mixture characterisation methods, to analyse the samples and evaluate the different rubberised bituminous mixtures' mechanical and impact-attenuating performances. The laboratory test and their order are schematised in Figure 4. The developed protocol includes geometrical and volumetric analysis, and mechanical, abrasive and impact-attenuation tests.

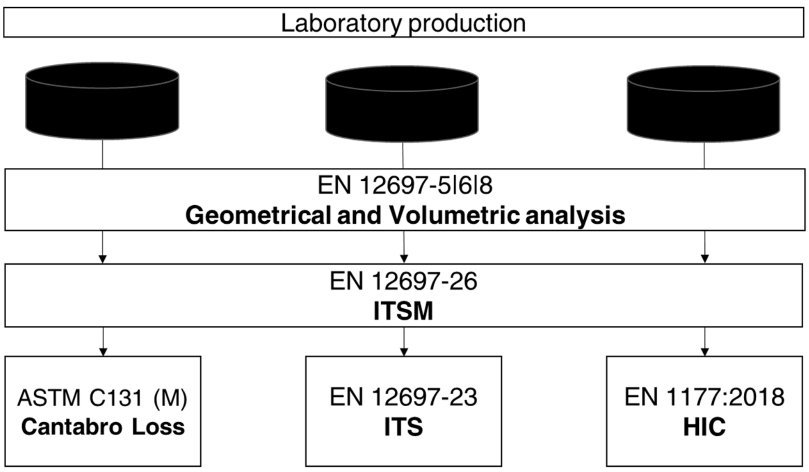

Figure 4. Developed testing procedure for the assessment of the basic performance of IAP.

2.5.1. Geometrical and Volumetric Analysis

After producing the cylindrical samples, the first characteristics to be measured were the weights and dimensions. After compaction, the vertical and horizontal expansion, which mainly occurred due to rubber swelling, were also measured. Indeed, after compaction, an internally measured height value was given by the compactor. This height was verified manually a few minutes after compaction, and an expansion was recorded. This manual measurement was also repeated 15 days and 1 month and 6 months after the time of the samples' production.

2.5.2. Cantabro Loss Test

The Cantabro loss (*CL*) method [15] is generally used to determine the abrasion loss of compacted asphalt samples using the Los Angeles abrasion machine. This machine can induce the loss of abraded material via rotation for several cycles at a fixed speed (30–33 rpm for 300 revolutions).

The *CL* can function as an indication of the durability and the resistance to abrasion of the sample by means of the following equation:

$$CL\ [\%] = \frac{m_i - m_f}{m_{fi}} \times 100 \tag{1}$$

CL: Cantabro loss (%)
m_i: the initial mass of the specimen (g)
m_f: the final mass of the specimen (g)

Only the IAP 2 and REF AC (as the first produced samples) were tested using the Cantabro loss testing procedure. This was because of doubts that arose regarding the method's effectiveness for the designed samples. This doubt was clarified later, thus confirming the Cantabro test method as effective for testing highly rubberised IAP samples.

2.5.3. Indirect Tensile Stiffness Modulus (ITSM) and Indirect Tensile Strength (ITS)

The preliminary mechanical characterisation was mainly performed by employing the Indirect Tensile Stiffness Modulus (ITSM) [13] and the Indirect Tensile Strength (ITS) [14] tests on cylindrical samples. These are very common and referenced testing methods for compacted samples of asphalt concrete. The ITSM, determined by the IT-CY method, is a non-destructive test that provides data on the stiffness of the sample at a specific temperature (it was conducted at 5 °C and 10 °C), while the ITS measures the maximum tensile stress, calculated from the peak load applied at failure of the sample. The ITS test was conducted at 10 °C and 25 °C.

2.5.4. Head Injury Criterion (HIC)

Several injury criteria exist to determine the effects of a collision, a fall or an impact as the origin of injuries. The neck injury criteria (NIC), the tibia index (TI) and the HIC related to head injuries [19]. Determined after a series of tests on cadaveric heads in the 1960s, this value is nowadays derived from the measurement of acceleration and fall time thanks to accelerometers and sensors inside of an artificial concentric head (approx. 5 kg in mass). The falling device simulates a simplified version of adult human head behaviour during an impact. Frequently used in impact sports or collision studies, the HIC is an excellent indicator of the damage that could be caused on the skull and brain, and it is defined as:

$$\mathrm{HIC} = \left\{ \left[\frac{1}{t_2 - t_2} \int_{t_1}^{t_2} a(t)\, dt \right]^{2.5} (t_2 - t_1) \right\}_{max}, \tag{2}$$

t_1: start time
t_2: end time
a: acceleration

To test the IAPs, the present study used testing methods that were established for the assessment of the impact-attenuation properties [10], and which are usually employed to measure the impact attenuation of surfacing materials. A scheme and pictures of the test device and the testing set-up are shown in Figures 5 and 6, respectively. Through the measurement of the severity of a head injury that is likely to arise from an impact, i.e., HIC, the method allows the calculation of the critical fall height (CFH) of the pavement and the maximum Free Height of Fall for which a paved surface provides an adequate level of impact attenuation. A HIC lower or equal to 1000 is considered as an acceptable limit for playgrounds [11]. The HIC can also be related to the Abbreviated Injury Scale (AIS) used to classify injuries from abrasion (1) to a fatal injury (6) [20]. Table 6 shows the classification of the injuries according to the HIC values.

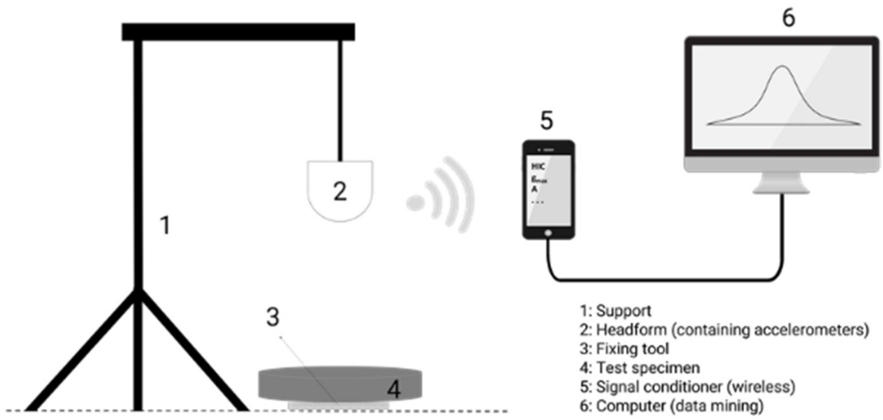

Figure 5. Scheme of the impact-attenuating properties testing method.

Figure 6. Pictures of the HIC test device installation ready for in-situ (**left**) and laboratory (**right**) testing.

Table 6. Abbreviated Injury Scale AIS classification of the injury type by HIC [20].

HIC	AIS Code	Severity	Description
>1860	6	Maximum	Fatal, not survivable.
[1859–1575]	5	Critical	Unconscious for >24 h; large hematoma
[1574–1255]	4	Severe	Unconscious for 6–24 h; open skull fracture
[1254–900] 1000	3	Serious	Unconscious for 1–6 h; depressed skull fracture
[899–520]	2	Moderate	Unconscious for <1 h; linear skull fracture
[519–135]	1	Minor	Headache or dizziness
<135	0	Null	No injury

The instrumented artificial head strikes the tested surface from different drop heights. The signals emitted by the accelerometers in the device during each impact are processed to yield a severity from the measured impact energy, defined as the HIC, and to determine the peak acceleration (g_{max}). The method determines the drop heights at which HIC is at a maximum of 1000 and the g_{max} is 200. This procedure is used to calculate the CFH of the impacted pavement [3].

The IAPs' samples were tested at different temperatures ranging from −10 °C to +40 °C to obtain an extensive range of values corresponding to the various climate conditions.

3. Results and Discussion

3.1. Geometrical and Volumetric Assessement

For each mix, a minimum of three replicates were produced to perform the planned tests. The preliminary visual assessment and test measurements provided valid initial information on the overall performance of the rubberised samples. Specific geometrical and mass measurements allowed the calculation of the specimens' densities and air void content. The results are listed in Table 7.

Table 7. Densities and air voids content values for each tested mixture.

Mixes	EN12697-6 D Density (g/cm^3)	EN12697-5 B Maximum Density (g/cm^3)	EN12697-8 VA (%)	EN12697-8 VMA (%)	EN12697-8 VFB (%)
REF AC	2.273	2.207	2.9	33.7	91.4
IAP 1	1.740	1.605	7.8	38.0	79.6
IAP 2a	1.460	1.383	5.2	38.9	82.8
IAP 2b	1.541	1.423	7.7	42.4	80.3
IAP 2c	1.654	1.586	4.1	30.1	90.4
IAP 3	1.443	1.371	5.0	33.7	83.4

All compacted samples were in satisfactory initial conditions and their inner cohesion and adhesion appeared to be sufficient to keep the lithic and rubber particles together after the extraction from the compaction mould. The specific weight of IAP specimens containing high amounts of rubber was approximately 1/3 less than the reference asphalt concrete specimens' value. Figure 7 directly compares the two pictures of the reference standard asphalt and the IAP 2a specimens.

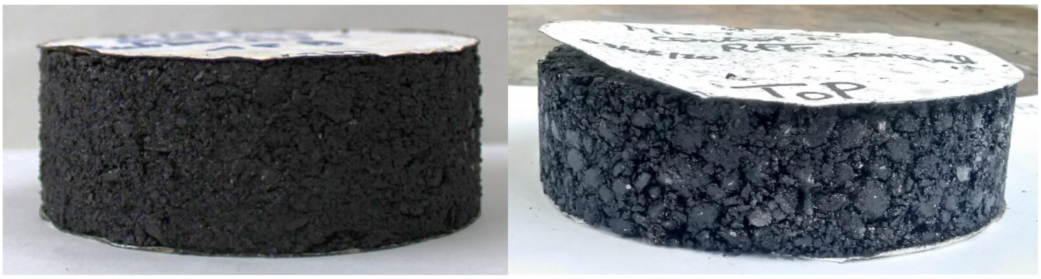

Figure 7. Overall aspect of compacted IAP 2a (**left**) and reference AC (**right**).

The geometrical measurements of the specimens showed an anisotropic volumetric expansion that occurred independently of the origin or type of rubber and bitumen. This phenomenon was due to the content of the rubber, its elastic recovery after compaction, and the swelling reactions that occurred due to the bitumen/rubber interactions. This expansion also caused the loss of some rubber particles from the external specimen surface after compaction. The expansion developed with a high-volume rate change, directly after compaction, and slowly faded with time. Figure 8 describes the development of the vertical expansion one month and six months after the time of production for most of the mixes.

This phenomenon was hardly visible with the AC reference samples, while it was more evident in the rubberised samples. The average expansion value of IAP 3 was lower than those of IAP1 and IAP 2a, despite containing more rubber in terms of percentage. However, IAP 3 contained coarse aggregates while IAP 1 and IAP 2a did not. By reducing the available surface and porosity for the diffusion causing the swelling, this phenomenon, initiated between the bitumen and the rubber, was reduced, and expansion of the sample was consequently limited.

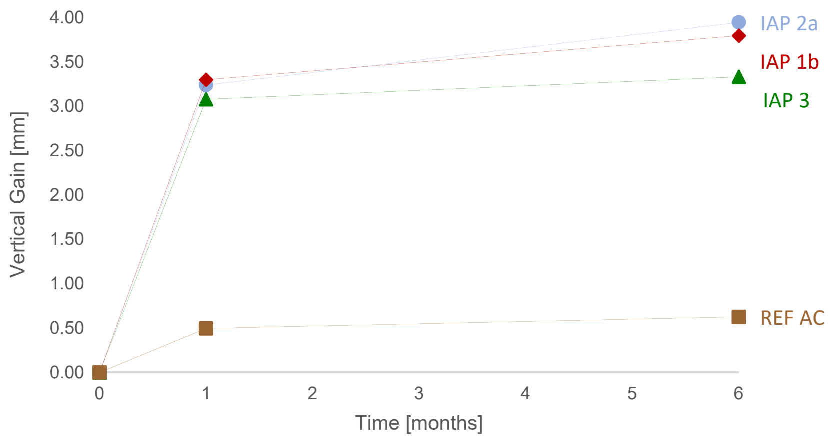

Figure 8. Vertical expansion after one month and six months for the mixes REF AC, IAP 1, IAP 2a and IAP 3.

3.2. Cantabro Loss and Abrasion Results

Figure 9 shows that the material abrasion was reduced (by approximately 4–5 times) for the reference sample as compared to the rubberised samples. This seemed to be caused by the addition of high quantities of rubber in the mix, which provided elastic properties to the samples that could partially bounce inside the Los Angeles apparatus. Even if the binder significantly influenced the particle's loss, the difference between IAP 2a (18% wt. binder) and IAP 2b (21% wt. binder) was negligible. Although the severity of the tests seemed to be reduced with bouncy samples, the results of the rubber specimen were still noteworthy.

Even if the test was conducted only for the REF AC and IAP 2 samples, the results with IAP 3 would most likely be comparable to those of IAP 2a. and with IAP 1 having higher loss values than the IAP 2 samples.

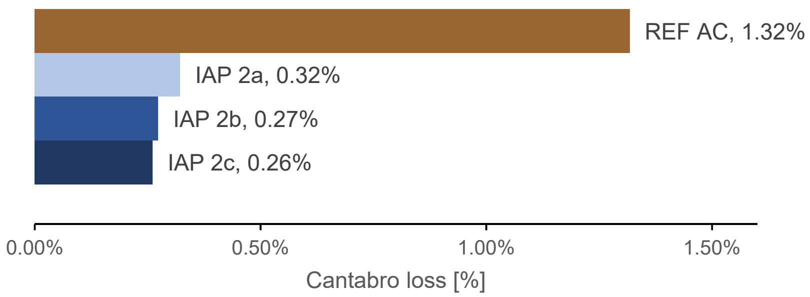

Figure 9. Cantabro loss showing the abrasion properties of the tested specimens.

3.3. Pavement Mechanical Performances

ITSM and ITS tests could give valid insights into the stiffness modulus and the required stress for the initiation of tensile cracking of the sample. However, even if the tests were conducted at cold temperatures, it was challenging to measure consistent values. The prominent elastic behaviour of the material influenced the actual observation of the cracks and, thus, the effective value of the indirect tensile strength. Table 8 shows that at 5 °C, the mechanical properties of the rubberised asphalt differed from the reference material and the stiffness was considerably reduced by the addition of rubber even at low test temperatures (5 °C and 10 °C). The obtained modulus was reduced by more than six times when comparing the reference material with IAP 3, the mix that had a higher quantity of rubber (Table 8).

The tested samples gave promising results in terms of the final objective of reducing the impact severity by decreasing the material's stiffness. Alternative methods such as direct tensile, stress relaxation and compression tests are foreseen to improve and optimise the mechanical measure of the rubberised materials.

Table 8. Average tensile strength and stiffness modulus of the different mixes.

Mixes	Indirect Tensile Strength (MPa) 10 °C	Indirect Tensile Strength (MPa) 25 °C	Stiffness Modulus (MPa) 5 °C	Stiffness Modulus (MPa) 10 °C
REF AC	2.69	1.78	12,496	11,654
IAP 1	0.91	/	1236	/
IAP 2a	0.36	0.35	301	229
IAP 2b	0.51	0.31	273	194
IAP 2c	0.48	0.26	202	124
IAP 3	0.44	0.29	248	/

3.4. Attenuation of Impacts and Injury Prevention

3.4.1. Influence of the Rubber Amount

The use of CR in large quantities had a beneficial effect on the circular use of tyres, the recycling of the rubber and the elastic properties of the newly formulated impact-absorbing bituminous material. The IAP 3 samples attenuated more the impacts than the IAP 2, IAP 1 or REF AC samples. Indeed, from the same dropping height, the AIS code was reduced to 0 (null) with IAP 3, while it was 3 (severe) for the REF AC samples (Table 9). Moreover, as shown in Figure 10, by increasing the amount of rubber, the drop height could be increased, albeit still recording lower HIC values than those obtained from the REF AC. A rough direct relationship can be seen between the increase in impact-absorbing properties and the quantity of rubber.

Table 9. HIC and related AIS code corresponding to the fall for each specimen from an equal drop height (0.2 m) at T_{amb}.

Mixes	%Rubber (wt.)	Drop Height (m)	HIC	Standard Deviation HIC	Related AIS Code
REF AC	0	0.2	1111	6	3
IAP 1	14	0.2	470	46	1
IAP 2a	28	0.2	160	17	1
IAP 2b	27	0.2	170	19	1
IAP 2c	27	0.2	109	9	0
IAP 3	33	0.2	114	5	0
* PLAYGROUNDS	>50	0.2	22	/	0
* RUBBER CONCRETE	20–30	0.2	195	/	1

* Values obtained in preliminary studies [4].

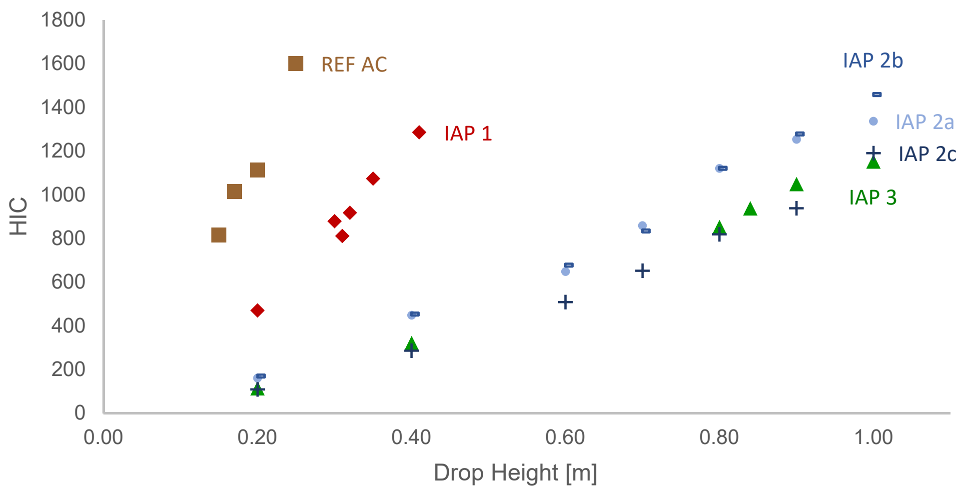

Figure 10. Laboratory HIC values when increasing the dropping height at room temperature (22 °C ± 1 °C).

Furthermore, the head impact altered the REF AC sample surface after several drops, while the IAP 3 sample was almost intact. This can also be considered a positive outcome in terms of the surface durability of the highly rubberised samples. The pictures in Figure 11 clearly support these observations. White tape was used as a tool to delimitate the impacted zone during the HIC test. The impacted zone for IAP3 was higher. This variation was due to the need to modify the test head height more often than for the reference (higher drop height). Thus, the impact zone precision was lower, while the REF AC needed a few set modifications during the test. However, at a lower drop height, the surface of the REF AC was more degraded. Therefore, the achievement of the required impact-absorbing properties did not negatively affect the surface durability of the material.

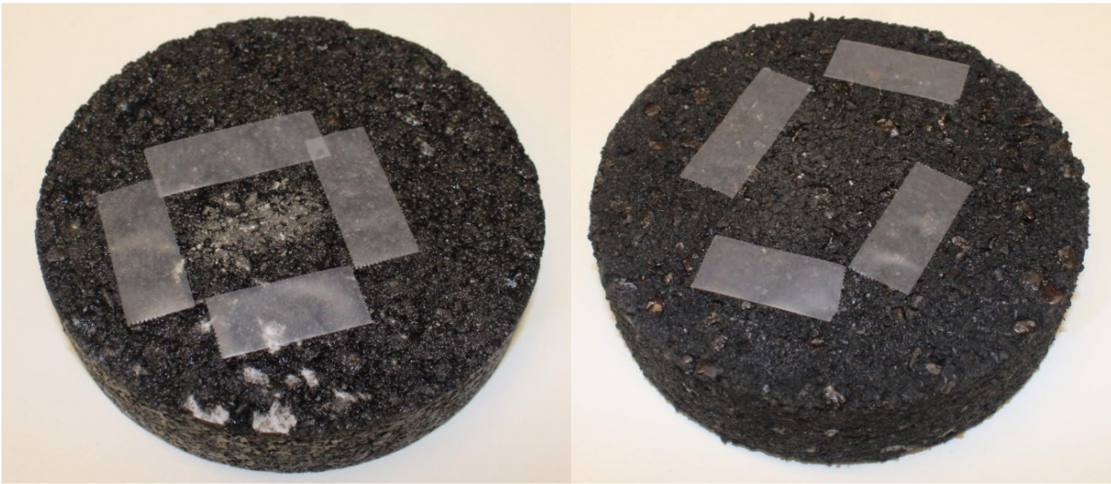

Figure 11. Tape-delimited impacted zone after several drops of the HIC-meter head: REF AC (**left**); IAP 3 (**right**).

3.4.2. Influence of the Testing Temperature

In addition to the rubber quantity, the temperature had a considerable influence on the measured HIC values. Consequently, the CFH was also affected by temperature. Intuitively, for these kinds of visco-elastic materials, the impact-attenuating properties at 40 °C are higher than those at −10 °C. All the test results are shown in Figure 13.

Even if Figure 13 clearly shows that IAP 2c had better attenuation properties than IAP 3 at 40 °C, the influence of the rubber variable was predominant over the binder dosage one. When the amount of bitumen increased, the sample with the largest quantity of bitumen for a given volume of rubber exhibited a slight increase in the CFH values at high temperatures. In general, the targeted amount of bitumen should be as low as possible to limit costs. Moreover, the CFH at −10 °C or −2 °C for IAP 3 was still higher than the CFH of IAP 2c at the same temperature and the CFH at +40 °C for IAP 1. As the IAP 2 and IAP 3 mix had similar behaviour, IAP 3 was found to be preferable as an impact-absorbing material for the above-mentioned reasons.

3.4.3. Influence of the Testing Layer Thickness

To evaluate the thickness influence on the HIC values, samples were assembled by simple superposition in the laboratory, as shown in Figure 12. Hence, the IAP 2ab (approx. 90 mm) and IAP 2abc (approx. 130 mm) compositions made it possible to compare the behaviour of HIC and CFH with different layer thicknesses. Double sided adhesive was used between the samples.

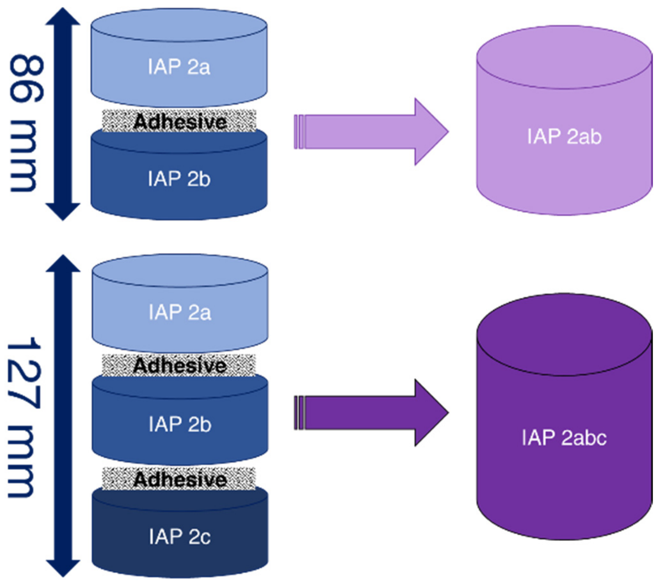

Figure 12. Scheme of the samples assembly to assess the influence of the layer thickness.

Augmenting the layer thickness from 4 cm to 9 cm increased the CFH values by approximately 0.5 m. Besides, when the layer height was increased to 13 cm, the CFH values were approximately doubled, as shown in Figure 13.

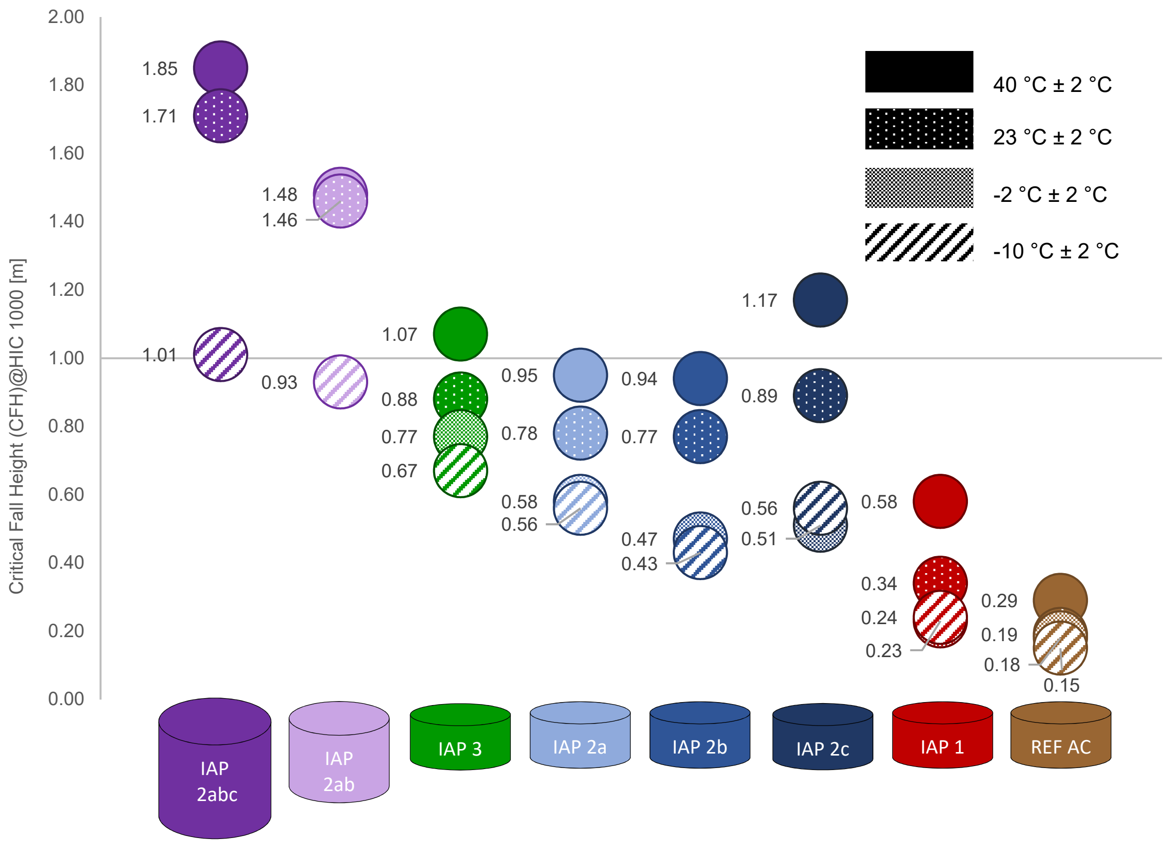

Figure 13. CFH at HIC = 1000 including IAP 2abc and IAP 2ab @ four temperatures: −10 °C, −2 °C, 23 °C and 40 °C.

Even if the 4 cm thick IAP 3 sample had a positive effect in terms of lowering the AIS code to 0 and, therefore, approached the recommendations for playgrounds (i.e., Table 9), the goal for the present application was to have a CFH above 1 m (even at low temperatures). In fact, a CFH higher than 1 m is considered as the minimum requirement for validating the formulation as adequate in terms of reducing injuries from VRUs' falls. The objective is to be far below the reference value of the concussion HIC 1000 [21].

4. Conclusions

The laboratory work performed on the different formulations provided noteworthy results. The main relevant and preliminary conclusions that can be drawn are as follows:

- Adopting the dry process method made it possible to produce samples with a rubber content larger than 30% total weight (larger than 50% total volume). Those bituminous samples also contained coarse crumb rubber particles (0 mm to 4 mm size).
- The bitumen quantity should be kept as low as possible for a given rubber amount as the CFH variation observed between the IAP 2a 2b 2c and IAP 3 was not significant.
- The swelling reaction played a role in the geometrical expansion of the material. However, the addition of a high amount of rubber did not cause critical abrasion behaviour when tested with the Cantabro loss method. The percentage of loss was four times less than the reference asphalt, but future work will have to specifically assess the reliability of the applied test method.
- As a result of ITSM measurements, it was observed that for the IAP 3 samples containing 33% wt. rubber, the stiffness modulus was 40 times smaller than the reference asphalt. Additional stiffness or mechanical tests are needed to investigate different testing method or conditions (i.e. simulating different climates).
- The greater the amount of rubber that was added, the higher the impact-attenuation effect that was measured through HIC, and the higher the calculated CFH. The addition of rubber consistently enhanced this property even at low testing temperatures.
- The obtained HIC and CFH were approaching the recommendations for playgrounds. IAP 3 samples lowered the AIS parameter from 3 (REF AC) to 0, thus reducing the risk of severe injuries.
- The optimal thickness of the pavement rubber layer appeared to be between 4 and 9 cm. The thickest samples recorded auspicious results even at cold temperatures. Thicker layers can require multiple layers using the traditional paving techniques.

The obtained results align with the targeted material characteristics; however, additional work is required to investigate other temperature conditions, as well as durability and surface properties. Furthermore, the mechanical analysis must be improved and stress–relaxation or compression tests need to be incorporated within the mechanical characterisation procedure. The tests also raised interesting questions, especially regarding bitumen's actual role in optimising the required impact-absorbing properties in terms of its quantity, costs and actual sustainability. The use of alternative binders, possibly bio-based ones, will be considered a means of increasing the sustainability of the materials.

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