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Rubber- and emulsion-based impact-absorbing paving material produced with cold and dry processes: Laboratory and in-situ study

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ABSTRACT

Impact-absorbing pavements (IAPs) may be used as novel sidewalks and bike lanes surface layers to decrease fall-related injuries among vulnerable road users (VRUs). Therefore, a cold-made, highly rubberised asphalt mixture (56% recycled rubber in the total volume of the mix) was developed in the laboratory, and the process was then upscaled, permitting its construction on a trial site. Both laboratory and on-site tests facilitated the evaluation of the material's mechanical properties, impact-absorption capabilities, and frictional behaviour. The field trial enabled a comprehensive assessment of the material's performance after six months of usage by pedestrians and cyclists on a hybrid segment. Additionally, evaluations were conducted after six, fifteen, and twenty months. The results confirmed the possibility to produce and lay a cold, highly rubberised paving material with valuable impact-attenuation performances. The mechanical analysis has shown the material's elastic behaviour and its capability to carry uniaxial compression stress leading to a 5% strain of the total height without losing its properties. Furthermore, the critical fall height (CFH) values exhibited a sixfold increase compared to conventional asphalt, thereby reducing the severity of potential injuries. In terms of durability, the pavement's overall effectiveness remained significant even after six, fifteen, and twenty months of use. The study demonstrated the capability to cover and fill holes and damaged portions using the same rubberised and cold mixture, a crucial aspect concerning the material's future and maintenance considerations.

1. Introduction

The growing population and traffic in urban areas have led to remarkable changes in the development of road infrastructures. As the demand for new paving solutions increases, various studies on traditional and innovative road materials are being targeted.

Road paving materials are crucial for transportation infrastructures that occupy an important part of the human mobility ecosystem. Nowadays, one of the target of infrastructures research is to include innovative materials (also obtained from a circular economy approach) aiming to maximise recycling while providing mechanical performances and economic advantages and benefits [1,2]. In this context, pavements with novel and smart functions such as noise reduction [3] and vulnerable users' friendly impact-absorption [4] are also being developed.

Crumb rubber is recycled and is indeed, one of the material that can be used to successfully reach the two latter aspects just mentioned. In addition to its recycling impact [5–7], recycled rubber is known for its effectiveness in designing low-noise pavements or impact-attenuation applications, thanks to its residual elastic properties [8–10].Several studies on crumb rubber as a partial replacement of the mineral aggregates by using the dry process exist [11–13]. Nevertheless, the volume percentage of the replaced aggregates is limited [14]. This is because the goal and the final application are very different. Actually, when the rubber amount is limited, the objective is mainly to enhance the flexibility of the pavement for wheeled and heavyweight vehicles [15,16]. However, in the case of shock-absorbing pavements, the aim is to propose impact-absorbing surfaces for sidewalks, bike lanes and hybrid paved sections for safety reasons. Some work has already been made on the development of IAPs with more than 50% of crumb rubber in volume. Their ability to reduce fall-related injuries has already been studied. However, in these cases, only hot or warm mixing methods (both for concrete and asphalt) were tested and the data collection on the

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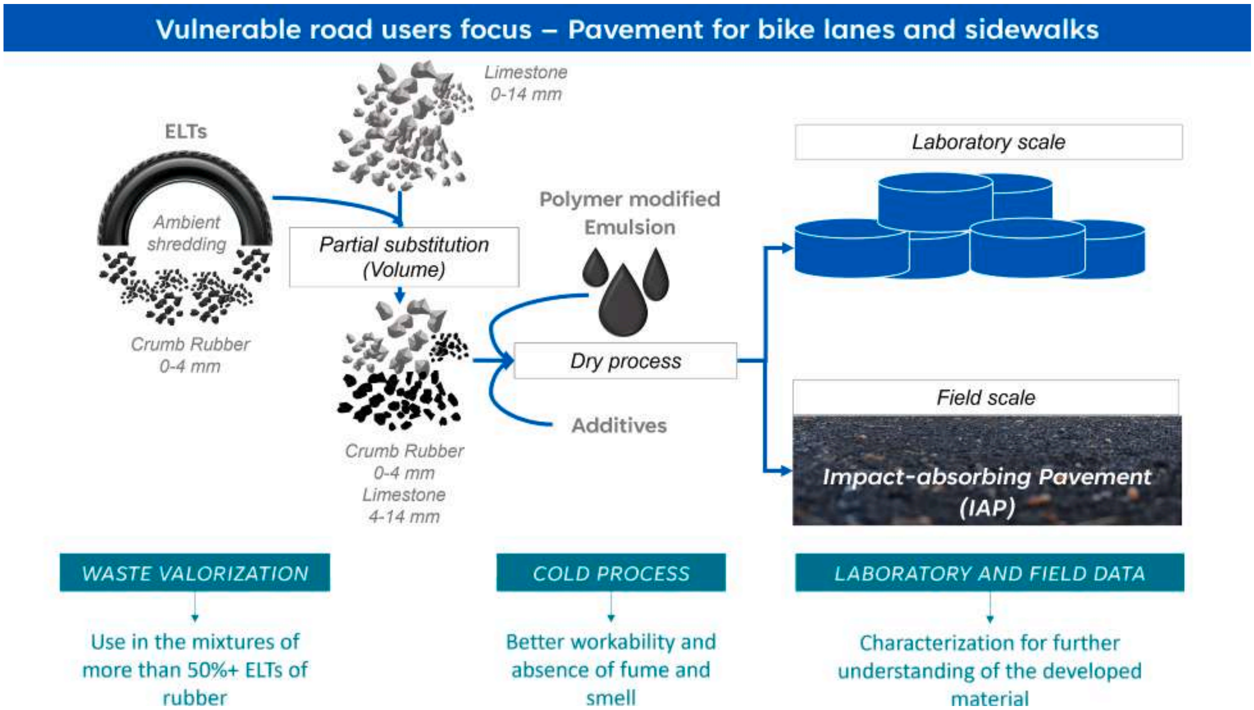

Fig. 1. Integration of the current study within the authors' research work pillars.

durability of the material over time in real-life conditions was limited [4,17–19].

This work aims to introduce a novel manner of producing Impact-absorbing pavement (IAP) using a cold process and to evaluate the mechanical, impact-attenuation and friction performances of the cold-made IAP material both at laboratory and field scale. The material is designed to reduce falls-related injuries and is intended for sidewalks and bike lanes in urban areas as illustrated in Fig. 1. The primary objective of this study is to execute and test the proposed solution within urban road context, thereby facilitating the construction of several meters of road surface under improved labour conditions [4,19]. The obstacles associated with such material lay in the necessity to maintain a feasible production and construction, aligned with established methodologies employed within the asphalt industry, specifically in the context of rubberised asphalt. Leveraging established methodologies and existent infrastructural resources, the envisaged progression of this novel material holds promises for enhanced future outcomes, especially about cost considerations.

2. Materials and methods

An overview of the research work, including the use of different constituents, the laboratory and field preparations and productions, and the corresponding characterisations carried out, is shown in Fig. 2. Further details are explained in the following sections. It is worth noting that the study is intended for materials designed exclusively for usage on pedestrian paths and bike lanes within urban settings. The developed material is very soft compared to traditional pavements; therefore, the testing plan required the adaptation of methods as conventional asphalt laboratory equipment may sometimes not be well-suited due to the pronounced elasticity of the material.

The selected starting mixture is based on a typical Hot Rolled Asphalt (HRA), also known for containing a relatively high quantity of fine aggregates compared to other standard mixes. The objective of the mix design is to replace a portion of mineral aggregates with a graded proportion of crumb rubber (0–4 mm). Therefore, a portion of the mineral aggregates (0–4 mm) is replaced by the same volume and particle size distribution of crumb rubber recycled from end-of-life tyres. The use of rubber is motivated by the objective to obtain an elastic material fostering the circular economy of tyres in the transportation ecosystem [20–22]. Then, the material contains an uncommon amount of rubber (over 50% of the total volume of the mixture) compared to other rubberised asphalt-based pavements [12,23]. Moreover, an SBS-modified emulsion is used enabling a cold production coupled with a dry mixing process for the rubber granules changing from the utilisation of hot and warm procedures used in previous studies. It increases the mixture's workability and makes it possible to avoid the release of smell and smoke, and it avoids stickiness problems. At first, several samples of the IAP material, of different sizes (A −150 mm and B-40 mm diameter), with different compaction levels (10, 20, 30 and 80 cycles), and with different extreme surface appearance and treatment (non-treated, simple treatment (emulsion), and aggregates treatment (coarse aggregates + emulsion) were produced in the laboratory to conduct mechanical characterisation, impact-attenuation tests using head injury criterion (HIC) concept, skid resistance and friction analysis. Then, the process was upscaled for the consideration of a small trial field to verify the full-scale feasibility and application of the material. On the small trial field, the HIC measurements were again performed one month after the construction. After six months of exposure to pedestrians, cyclists and weather, the surface friction was also assessed, and some measures and observations were made on the evolution of the surface and its appearance over time. Other measurements are planned to verify the impact-attenuation performances and the material's durability when laid in real condition. Furthermore, the collection of mechanical and friction results will allow the definition of acceptance criteria to further develop the IAP material for its application in cities. Moreover, its implementation would reduce the injury and cost related to the injuries of vulnerable road users (VRU) partially due to pavement surface [24–28].

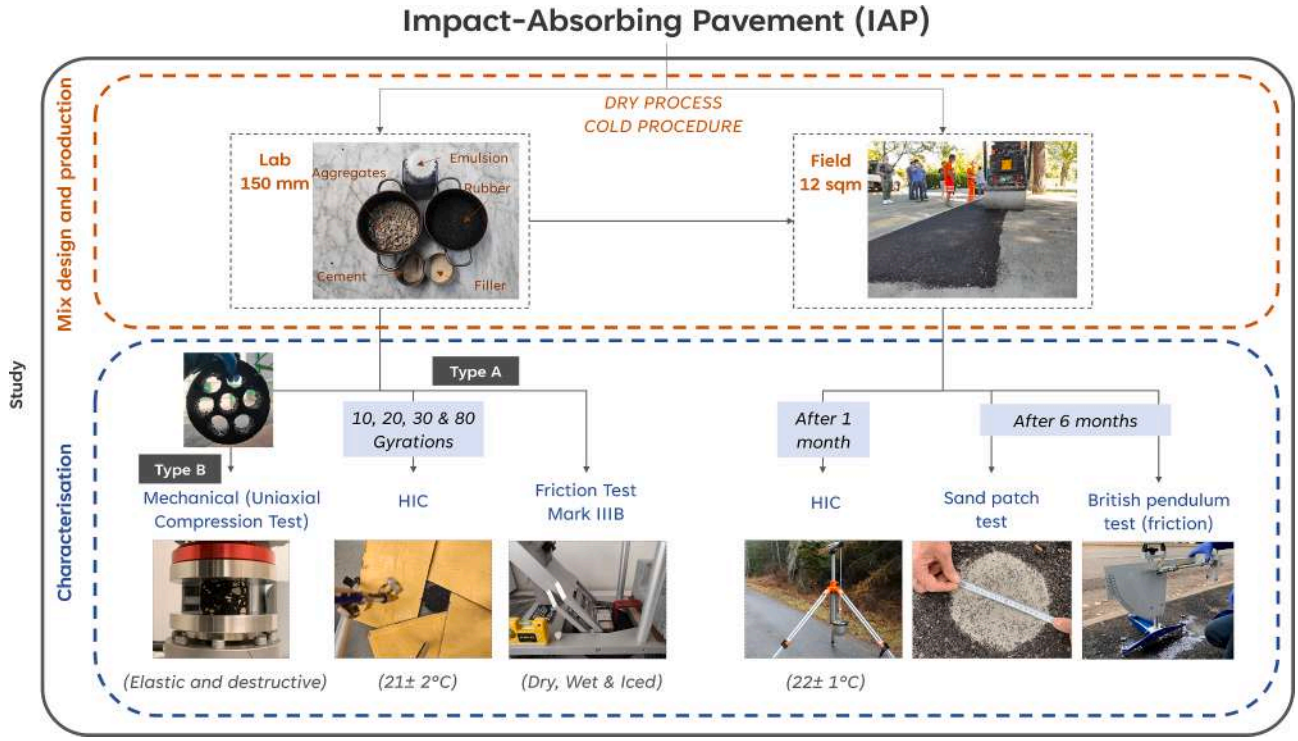

Fig. 2. Scheme of the conducted research plan.

2.1. Preparation and production of samples in the laboratory

Two types of samples were produced for laboratory characterisation. Type A samples were used for the laboratory HIC and Slip tests, while Type B samples were used for the mechanical tests (Fig. 2).

The IAP mixture is made of 56% by volume of crumb rubber (0–4 mm) recycled from end-of-life tyres in different sizes (Fig. 3).

Fig. 3. Image of the rubber mix used in the IAP formulation: Coarse (4–2.5 mm), Medium (2.8–1 mm), and Fine (1.2–0 mm) and SEM image of the mix used in the production in the field.

Table 1
Aggregates typical values.

Virgin aggregates (VA)	Particle size [mm] EN 933–1	Specific Gravity EN 1097–6
Limestone 1	8–14	2.661
Limestone 2	4–8	2.669
Limestone filler	$\leq$ 0.063	2.667

This mixture was produced by partially substituting the mineral aggregates (Table 1) portion (0–16 mm) with the same volume of rubber using a Hot-Rolled Asphalt (HRA) sieving curve as a reference (Fig. 4). The final mixture weight contains 46% wt. (22% vol) of aggregates (larger than 4 mm), 34% wt. (56% vol) rubber (smaller than 4 mm). The rubber mix is illustrated in Fig. 3 and the typical values are listed in Table 2. All the production was made at room temperature using the dry process coupled to a bitumen-based SBS-modified emulsion (PmE) with a dosage of 21% by total mixture mass. The emulsion's typical values are listed in Table 3. 1% wt. of cement was used as an additive to the mixture and breaking facilitator for the emulsion. The mixing process lasted 1–2 min to have a fully coated and homogenous mixture. This assessment was made using the organoleptic procedure described in EN 12697–55 [29].

The specimens were compacted using the gyratory compactor (150 mm diameter and approx. 40–45 mm thick). Multiple samples were produced for each number of gyratory cycles: 10, 20, 30 and 80 to compare the laboratory compaction to the field one. Finally, other samples were produced by modifying the surface characteristics to simulate the paving treatment intended to be used in the field site. These samples underwent surface coatings after compaction with a thin layer of:

- Transparent synthetic emulsion (Simple treatment (ST)) Fig. 5 (center),
- 3–4 mm aggregates and transparent synthetic emulsion (Aggregate treatment (AT)) Fig. 5 (right).

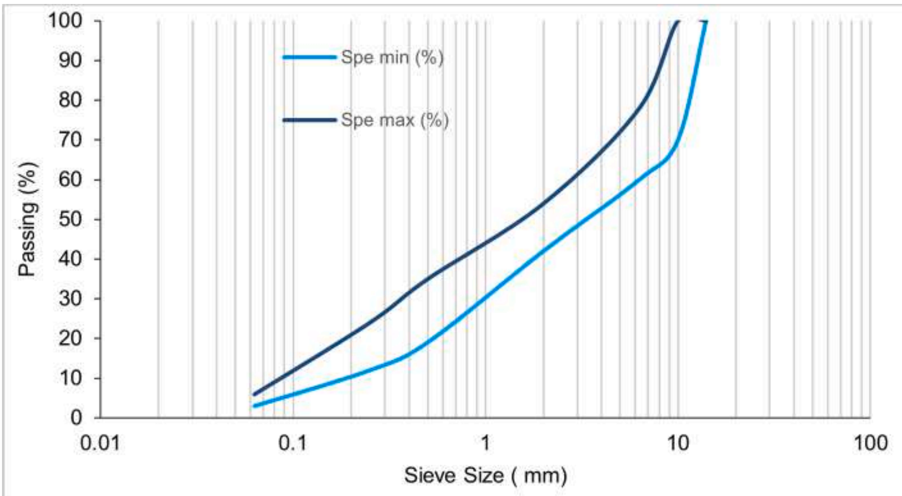

Fig. 4. Gradation curve of the HRA used as a reference for the design of the IAP.

Table 2
Crumb rubber typical values.

Crumb Rubber	Particle Size (mm)	Bulk Density [1] (kg·m3) EN 1097–3	Specific Gravity [2] EN 1097–6	PAHs 8 REACH [1] (mg/kg) (Specification ≤ 20)	Sum Total PAH 16 detected [2] (mg/kg) AfPS GS 2014:01 PAK
Fine (F)	0–1.2	0.44	1.028	6.5	Approx. 2.3
Medium (M)	1–2.8	0.44	1.028	6.5	
Coarse (C)	2.5–4	0.44	1.028	6.5	

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

Table 3
Emulsion typical values.

	Modifier	Binder Content	Breaking index	Viscosity at 40° C (cup discharge time 4 mm)	Adhesiveness	Penetration at 25 °C	Softening point
Standards		EN 1428	EN 13075–1	EN 12,846	EN 13,614	EN 1426	EN 1427
		%	-	sec	%	*dmm*	°*C*
Polymer modified emulsion (PmE)	SBS	63–67	70–155	5–70	≥ 90	45–80	≥ 60

Fig. 5. Samples with different surface treatments: Non-treated (NT); Simple treatment (ST); Aggregate treatment (AT).

For the mechanical tests, the compacted IAP samples were cored to a 40 mm diameter, as shown in Fig. 2.

2.2. Production of the IAP and trial site construction

For a material intended to be used as a pavement preventing injuries in urban areas, an *in-situ* trial is indispensable to validate the laboratory results, prove the repeatability and reproducibility and identify possible problems due to the upscaling of the process.

The same mixture produced in the lab was used to build a trial site in Imola, Italy (Fig. 6). The mixing, laying and compaction were done *in-situ* using traditional tools and machinery: mixer, paver (in this case electric) and roller compactor. As previously mentioned, the cold mixing procedure was preferred over the warm one used in previous studies [4,17] because it facilitates the mixture's workability and it avoids the release of smells and smoke, as well as avoids gluiness of the mixture.

The pavement laid was successfully tested for HIC and surface texture (British pendulum value and sand patch test). Furthermore, after

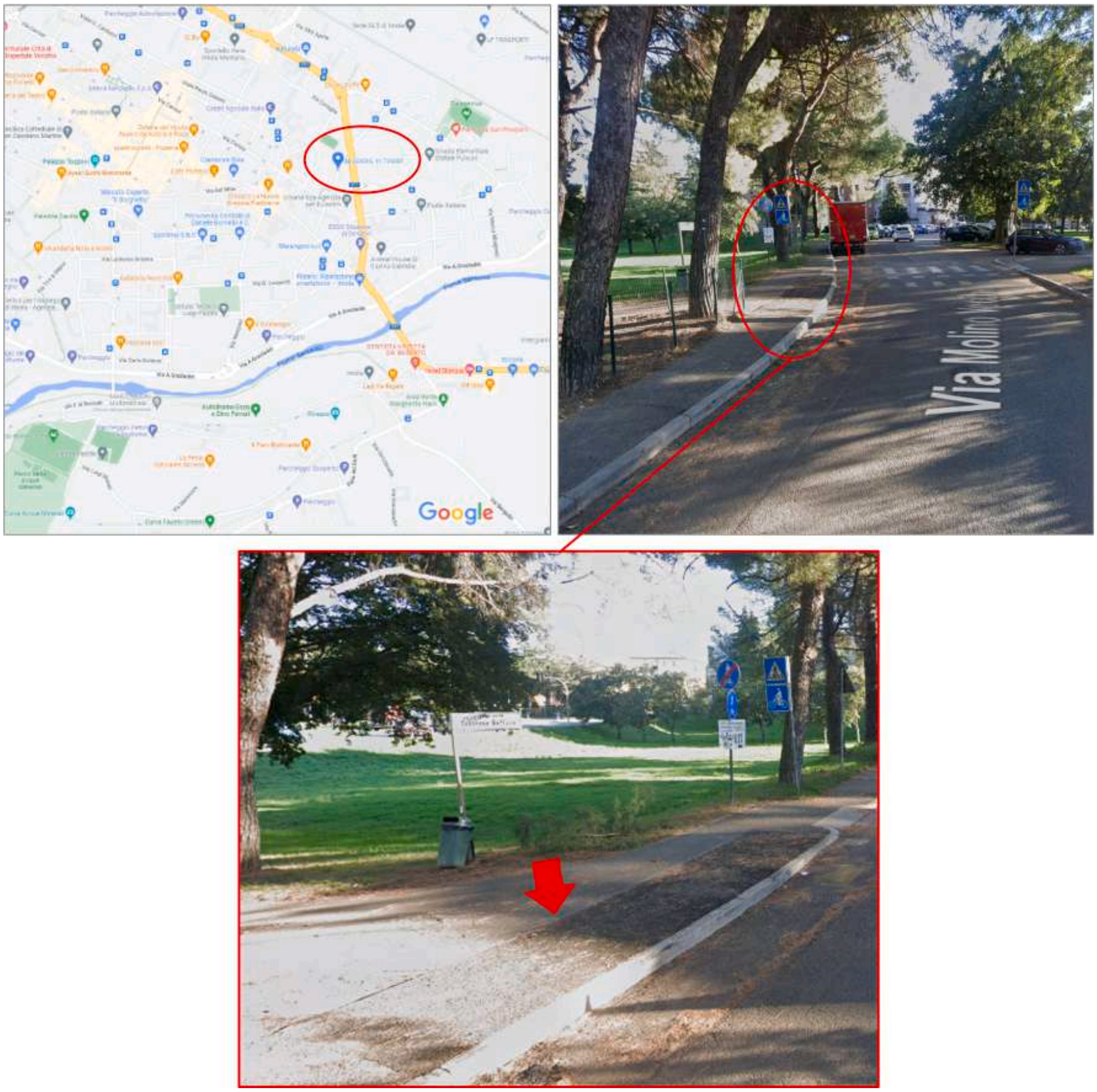

Fig. 6. Map and Picture of the 12 square meter trial site in Imola (Google maps).

six months of service, observations, coring, and patching of the holes were also conducted to simulate short maintenance of the paved section. The observations were also repeated after fifteen and twenty months.

2.3. Mechanical characterisation of the IAP

Two types of tests were performed on the samples: a compression-relaxation test by applying a small strain at time = 0 and holding it constant for 60 s (elastic test without permanent deformation (elastic test) and a compressive test until failure, both with quasi-static and dynamics vertical displacement rates (destructive test).

The uniaxial compressive stress-relaxation test on the type B samples was performed. For the non-destructive test, a constant stress was applied to reach 5% strain with a vertical displacement rate of 20 mm/min. For the destructive test, samples were compressed with a vertical displacement rate of 0.43 mm/s (QS), 43 mm/s (D1) and 430 mm/s (D2) to reach approximately 60% of deformation corresponding to the failure point of either visible cracks in the samples or maximum absolute stress in the stress–strain curve. The tests were performed at room temperature (approx. 21 °C) using an Instron Electropuls E3000 testing machine equipped with a 3 kN load cell.

2.4. Shock-attenuation performance of the IAP

The HIC drop test was conducted according to EN 1177 standard [30]. It was used to determine the material impact-attenuation performance at different compaction levels. The criteria of general protection standards are fixed by a peak acceleration of 200 g and a value of 1000 for the HIC. For adults, a HIC value of 1000 (chosen as a benchmark for playground surfaces) corresponds to an 18% chance of a serious skull injury, a 55% likelihood of a severe skull injury, and a 90% probability of a moderate head injury [4,31]. A hemispheric and concentric 4.6 kg impactor simulating the weight of a human head was released from different heights, and the impact speed and acceleration of the impactor were recorded. The same method was used in the laboratory and *in-situ*.

Regarding laboratory testing, the standard suggests a sample size of at least 250 × 250 mm. However, 150 mm diameter cylindrical samples were used due to the laboratory production configuration. A laser was used to point to the impact zone, as shown in Fig. 7. The samples were assumed to be on a rigid support and tested on the same laboratory ground.

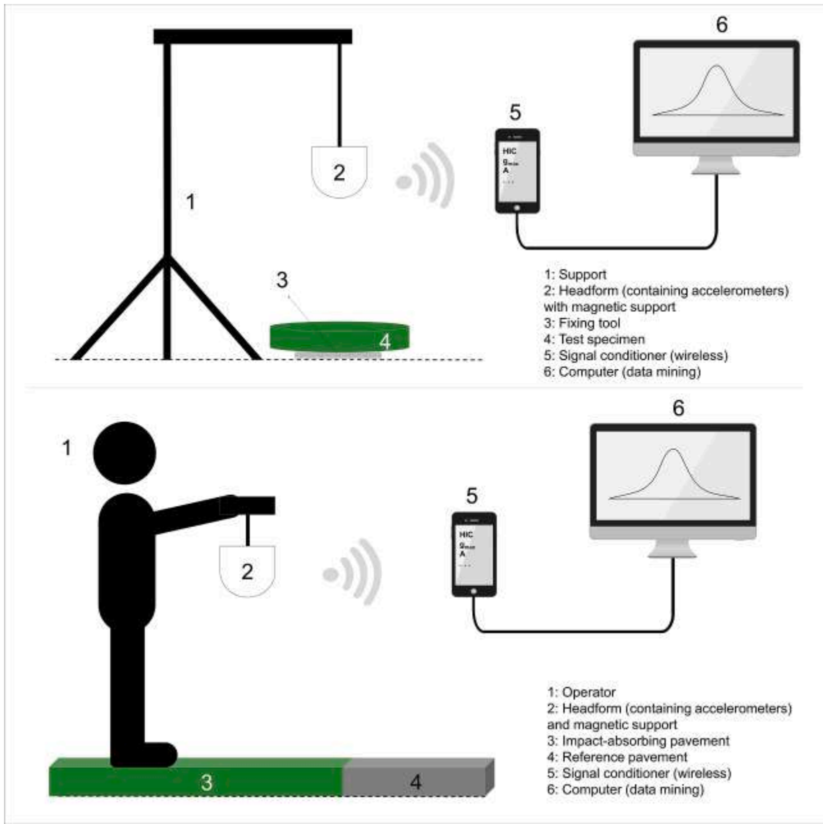

Fig. 7. Scheme of the HIC test in the laboratory and field setting.

2.5. *Surface analysis and friction behaviour of the material*

2.5.1. *Skidding analysis in the laboratory using a slip tester*

The road pavement's texture directly influences various indicators such as the tyres and sole wear in the case of cyclist and pedestrians.

Therefore, the measurement of the coefficient of friction (COF) between the shoe/sole and the pavement is essential in understanding the risk of slipping accidents. Therefore, the COFs of the same material with three different surface configurations were measured under three surface conditions: dry, water-wetted, and iced. The COF measurements were conducted using a Brungraber Mark IIIB slip tester, and a Portable Inclinable Articulated Strut Slip Tester (PIAST) [32] (Fig. 8 ***left***). It simultaneously applies parallel and normal forces to a surface by impacting a footwear sample on the material. The angle is increased until a slip occurs. The starting angle should be smaller than the angle at which the slip is anticipated, and the angle is slowly increased until the slip occurs. The tangent of the angle is the COF marked on the tester. The test was repeated at one location and averaged to better represent surface conditions.

This test was performed with four footwear materials: Flat rubber (FR), Textured Rubber (TR), Grooved Neolite (GN), and Grooved Rubber (GR), as illustrated in Fig. 8 ***(right)***. All materials simulate shoe (or bike) materials that may be used on-site.

This test, regulated by an ASTM standard, provides a preliminary outcome on the behaviour of the surfaces under different footwear and weather conditions, both in the laboratory and in the field. It also allows the evaluation of the surface by using footwear currently available on the shoe market.

2.5.2. *In-situ skidding resistance analysis using a British pendulum*

The skidding risk was assessed *in-situ* by mean of the British pendulum (Fig. 9) as described in EN 13036–4 [33]. This test was useful to estimate the risk and probability of skidding on an IAP surface.

2.5.3. *Sand patch test*

The method described in the EN ISO 13473–1 standard [34] and illustrated in Fig. 10 was used to determinate the mean texture depth (MTD) as well as the macro roughness and texture of the surface.

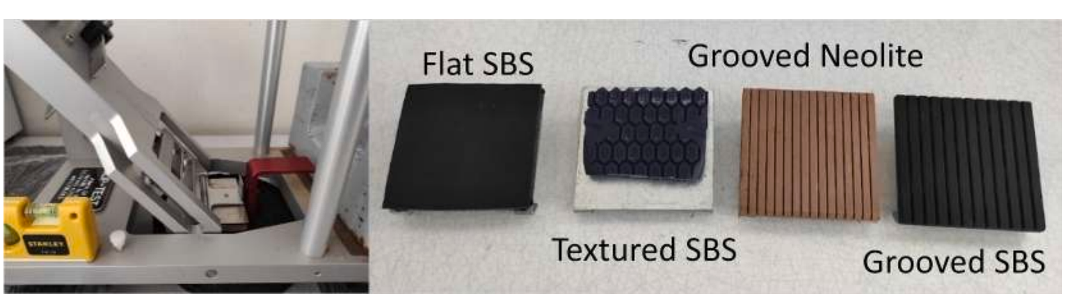

Fig. 8. Illustration of the Brungraber Mark IIIB slip tester and footwear sole used.

Fig. 9. British Pendulum test in-situ.

Fig. 10. Determination of the macrotexture depth according to the sand patch method.

Macrotexture primarily affect interaction between the road and the tyre or sole and correlate with numerous functional pavement attributes including the friction, and noise. These aspects impact safety, especially related to slip. This test is indeed useful for estimating the skid resistance and surface characteristics of the material or pavement treatment (ST or AT). In this case, it was intended to characterise the surface of the newly developed material in the field.

2.6. Inspection of the surface conditions of the trial field

The pavement was laid outdoor, and its evolution was visually tracked over time and it has been assessed at t = 0, 1, 6, 15 and 20 months. Fig. 11 shows the variations in temperature, rainfall, humidity, and UV index in the city of Imola, measured between June 2021 (t = 0) and December 2021 (t = 6) [35]. The surface was also inspected in September 2022 (t = 15) and February 2023 (t = 20).

3. Results and discussion

3.1. Mechanical performances

The compressive tests were conducted on 'Type B specimens' only due to the machine maximum load limit to assess the mechanical behaviour of the IAP. Both viscoelastic (relaxation) and destructive (strength) tests were carried out on the samples as described above.

Fig. 12 shows the graphical results of the tests carried out. Fig. 12 ***a*** and ***b*** respectively show the relaxation modulus over time and the compressive stress over strain of the samples. These results demonstrate that the samples have a viscoelastic relaxation response to an applied constant strain. Furthermore, it demonstrates that the stress–strain characteristics of the specimens resemble those observed in playgrounds [9,36], with stress levels spanning from 0 to 3 MPa. The specimens may imitate typical playground performance or potentially be perceived as softer, implying a higher likelihood of safety [9,36].

Indeed, the value of the stress decreases progressively over time. Moreover, the sample did not relax instantly after unloading and tended to retrieve back the original shape after a certain amount of time (in minutes). These results reveal that the material can be largely compressed, and this property is one of the main requirement for the impact-attenuation performance.

Concerning the compressive strength of the material, three different behaviours have been observed depending on the rate of load application. When applying a quasi-static load, the material elastic behaviour is more evident. However, the viscoelastic behaviour is dominant when a dynamic rate is applied showing a typical increase in stiffness with increased deformation rates Fig. 12 ***a.*** This observation is useful to show the absorbing effect of the material under compression as an important simulation of a fall-scenario on the material. Finally, after their failure, the relaxation of samples was still observed, and the specimens continued to show residual bounds at the rubber-binder interface. This has the potential to assure cohesion in situations involving daily usage and material degradation over time.

3.2. Impact-attenuation properties

To assess the impact-absorbing performance of the IAP, the standardised impact-attenuation test described above was used both in the laboratory and *in-situ*, as illustrated Fig. 2.

After performing various testing drops on the field IAP (different locations), the results show that the Critical Fall Height (CFH) calculated in the lab is similar to the one on-site. The IAP is six times more impact-absorbing than the traditional asphalt concrete. The CFH value increased from 0.2 m to an average value of 1.2 m in the field. Besides, the field and laboratory tests show that all values of CFH are above the standard-recommended limit of CFH = 1 m, regardless of the number of compaction cycles, even though it is possible to observe a decrease of the impact-attenuation performances with the increase of the compaction (i.e., density). As illustrated in Fig. 13 (left), the CFH *in-situ* (roller compaction) is closer to the CFH measured on the samples compacted with 30 cycles. Even if this method is simplified, it is possible to show that a fall could be less life-threatening if a cyclist or pedestrian falls from the critical fall height of 1.2 m.

Although the different accelerations measured by the HICmeter are not randomized the ones happening in the case of a real accident, previous studies showed, that similar CFH and HIC values were sufficient to considerably reduce the skull and hips fractures [4,37,38]. For instance, Fig. 13 gives a visual approximation of the drop height associated with HIC. This scheme also compares the HIC obtained with the Abbreviated Injury Score (AIS) score from 0 to 6 points [39]. This figure explains that if a person falls from 0.2 m (approximately the level of the shin/tibia) on a traditional asphalt pavement, the injury is classified as serious. Instead, if the fall occurs at the same height on the IAP, no injury will occur. This comparison shows the protective capability of the IAP material for its users in case of a fall. Also, previous studies conducted to compare the HIC measures showed that a similar material, made with the same quantity of rubber, provides a protective performance to prevent injuries, especially on the skull. This was done utilizing modelling and simulations of pedestrian and cyclist accidents [37].

Fig. 11. Weather measurements from June 2021 to December 2021 in Imola, Italy [35].

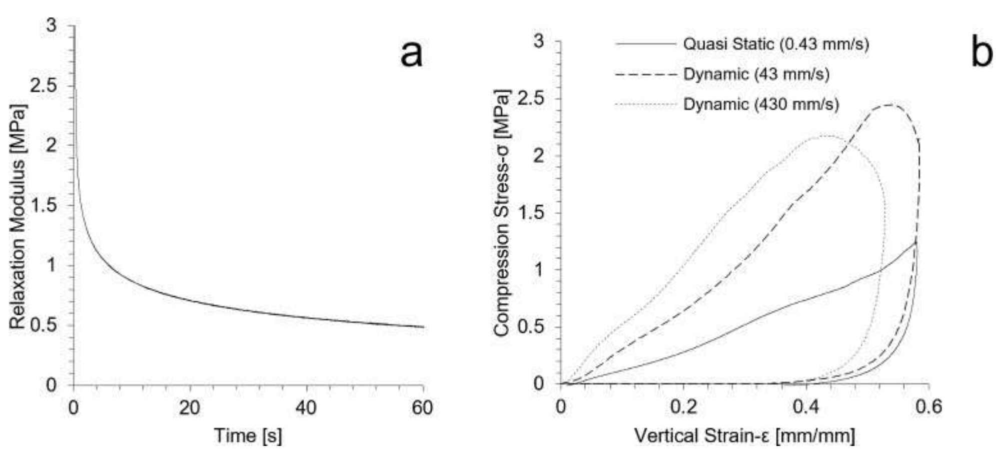

Fig. 12. Mechanical properties of the IAP material. a. Relaxation stress - time; b. Compression Stress - vertical strain.

3.3. *Friction values*

3.3.1. *Macrotexture*

To obtain information on the surface macrotexture, the sand patch test described by EN ISO 13473–1 [34] was used. The average diameter of the circle was 180 mm with an HS of 1 mm, as shown in Table 4. The laid IAP has a macro-roughness categorised as Coarse, and it can be associated with a large texture, that is in line with the expected results and several in-use real bike lanes pavements of the area [4]. Moreover, it has also been demonstrated in a parallel study that using crumb rubber as an aggregate showed no significant variations in the texture indicator compared to other mixtures made with 100% mineral aggregates

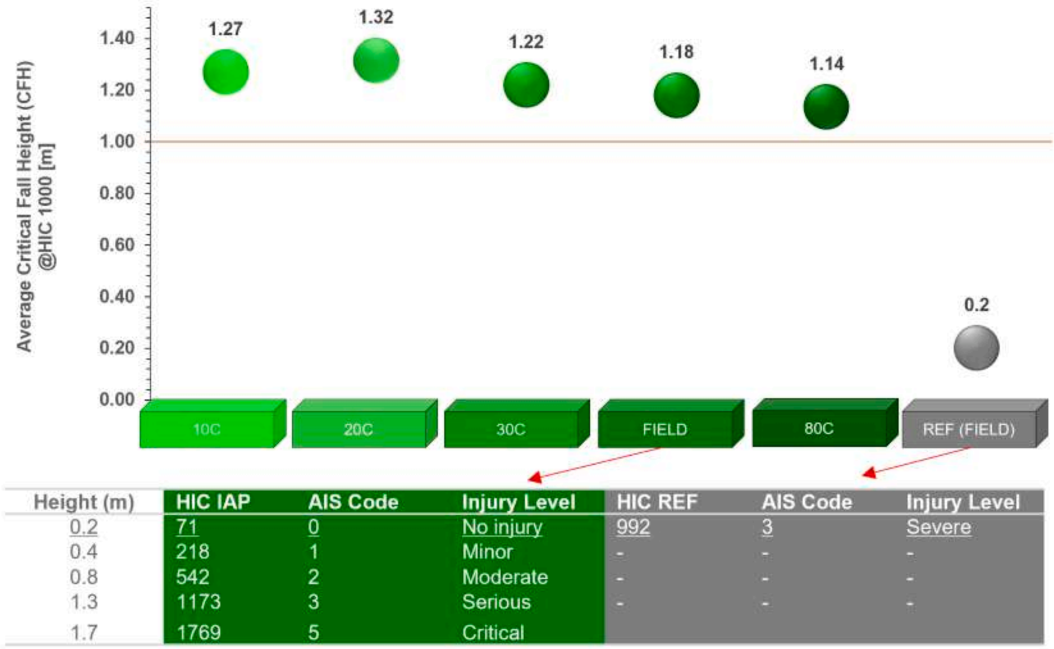

Fig. 13. Impact-attenuating performances of the IAP material.

Table 4
Results of the sand patch test after six months of service.

Location	Diameter [mm]	HS [mm]
Site 1	180	1
Site 2	180	1

sharing the same granulometric distribution. Yet, such surface can be problematic for injury caused by friction of the skin and scalp with the pavement. Therefore, this will require further studies [4,40].

3.3.2. *Slip risk and coefficient of friction*

To confirm the results observed in the visual and macrotexture characterization, slip tests were conducted in the laboratory and *in-situ*. Furthermore, it helped to assess the performances of different surface configurations and the surface behaviour under several conditions. Therefore, the laboratory slip test was conducted on three types of samples made with the same mixture but with different surface treatments: Non-Treated (NT), Simple Treatment (ST) and Aggregate Treatment (AT) as mentioned above. This because the relationship between the measured COF and the conditions of footwear, floor, and surface has previously been determined [41]. Also, the samples were tested under three different temperature conditions as described in the Methods section. Additionally, four different footwear soles simulating different kinds of materials used by pedestrians or cyclists. The test procedure is described in the Methods section. Fig. 14 illustrates all the obtained Coefficients of Friction (COF).Fig. 15..

On a dry surface, the COF is higher when the footwear sole is made of rubber. The ST does not affect the surface considerably; however, for the AT sample, no matter the footwear, the slip risk was lower. With the textured rubber (TR) footwear, the slip risk is the lowest, while the highest occurs with the grooved neolite (GN) material. All combination registered a higher average COF than the scenario presented in Li et al. study, also variating the sole material, type floor, and the surface condition and succeed in exceeding the 0.5 COF common safety standard [32] independently of the combination.

The same observation was made regarding the sole material tested on wet surfaces. The COF is higher with the SBR or SBS -based ones. Nevertheless, with this condition, the ST affect the surface by slightly decreasing the COF. This is not observed with the TR material. Also, on a wet surface, the COF observed on the AT samples is similar to or higher than on NT ones.

On the iced samples, an important reduction of the COF was observed, especially when the samples were tested with the rubber-based test sole. In the case of the GN material, this decrease is lower. The NT samples register the best COF values. The ST samples obtained very low values, and all under the 0.5 COF safety limit, this shows that when the surface is frozen it can be dangerous. Thus, two distinct behaviours were observed. For the flat rubber (FR) and TR, the surfaces were more slippery with the AT than the ST. However, the same surfaces (AT and ST) were less slippery for the two grooved soles. In this case, the grooving may have played a role in reducing the slippery effect of the aggregate-treated surface.

3.3.3. *BPN value and skidding risk in-situ*

Skidding has a role in the cyclists' or pedestrians' potential falls that lead to injuries. Thus, the skidding risk was also evaluated *in-situ* via the pendulum test described before. The average value of BPN of the IAP is very high (Table 5) and corresponds to a very low risk and probability of skidding with an SBR or SBS rubber-made footwear on a wet surface. This value is in line with the ones registered with the slip test in the laboratory. It is also supported by the macrotexture characterisation that categorised the pavement texture as coarse.

3.4. *In-situ observations*

Following the completion of the experimental pavement construction, visual assessments were conducted, accompanied by walking and biking trials. These evaluations confirmed the pavement's appropriateness for both activities as shown in Fig. 16.

Six months later, encompassing the period from June to December 2021, which covered the summer and autumn seasons, a visual examination of the surface was undertaken. The weather conditions occurring during the testing phase are shown in Fig. 11. Fig. 17 "a" illustrates the pavement's condition the day after its installation, while Fig. 16 "b" portrays its state after six months. These observations were also repeated after 15 months (September 2022) and 20 months (February 2023).

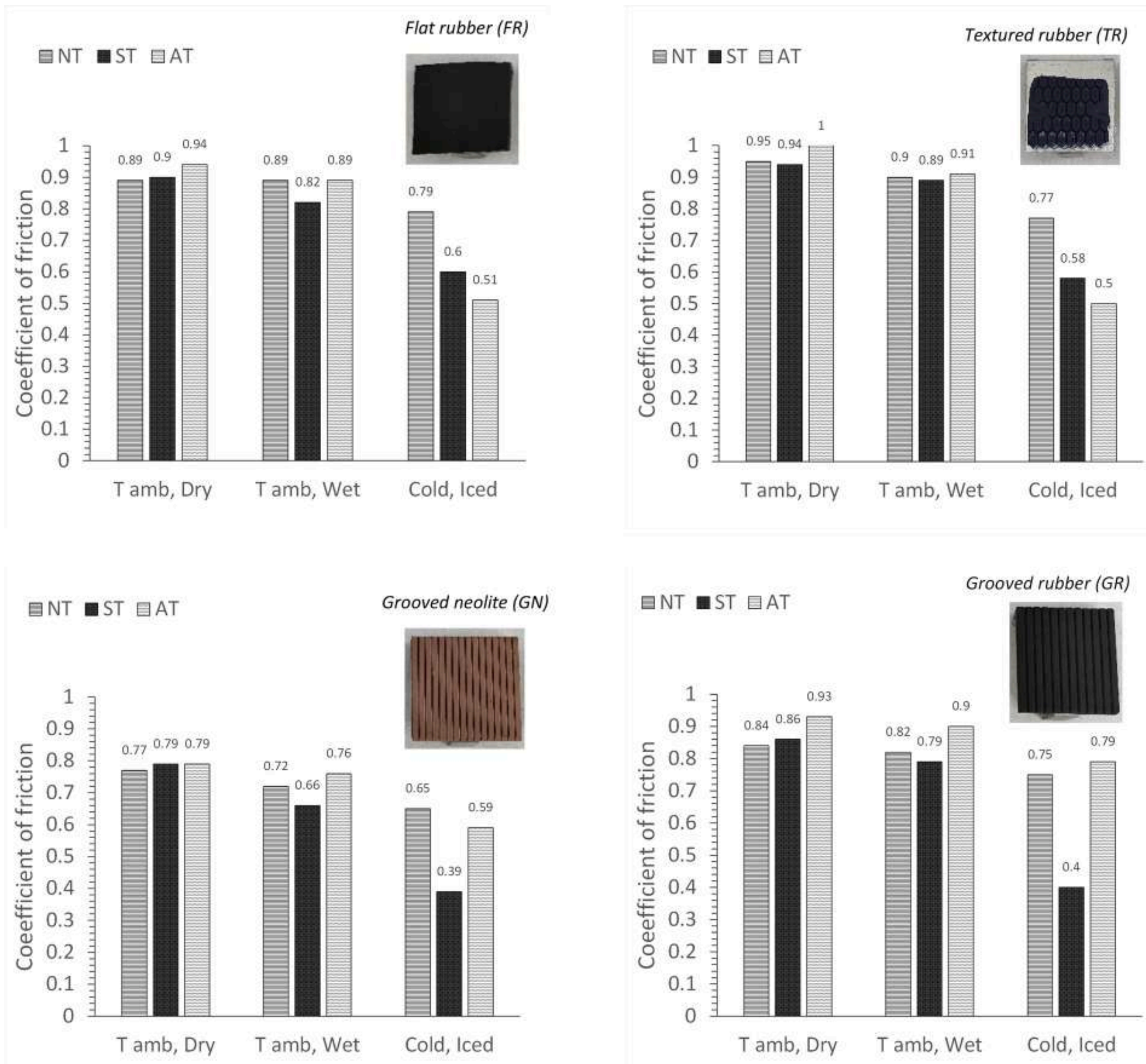

Fig. 14. COF of the different samples (non-treated (NT), simple treatment (ST) and aggregate treatment (AT)), tested with different footwear pads (FR, TR, GN and GR), and 3 different surface configurations (dry, water-wetted and iced).

Fig. 15. Walking and biking trials on the IAP after its construction.

Table 5
Values of the BPN measurements.

Location	Readings (BPN EN 13036–4)					Temperature [°C]	Average	Temperature Correction	Corrected Value
Site 1	82	85	87	87	87	11	85.6	−1	84.6
Site 2	78	78	77	80	80	11	78.6	−1	77.6

Fig. 16. Visual assessment conducted on the experimental surface at the following time points: a. June 2021 (m1); b. December 2021 (m6, before core and maintenance); c. September 2022 (m15); d. February 2023 (m20). The core and maintained zone are represented by the red circles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

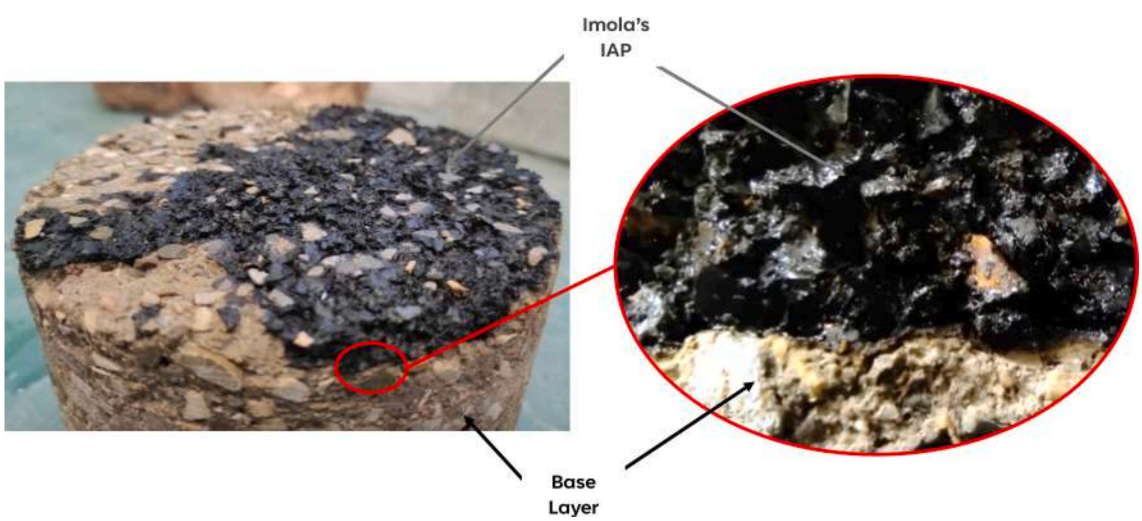

Fig. 17. Image of a core from the trial lane and a profile picture of the top layer (IAP) and base layer.

The overall material characteristics are conserved, and the IAP continues to be functional, accommodating both pedestrian and bicycle use even after a span of twenty months. Nevertheless, the comparison highlights a deterioration of the surface of the layer as illustrated Fig. 16.

During the production phase, reduced coating of the mineral aggregates has been detected, which can be one of the causes of the observed early stripping. This lack of coverage may be caused by compatibility issues involving the chemistry of the emulsion, rubber and aggregates, the texture, mineralogy, and surface behavior of the minerals [42–44]. Yet, this may also be coupled by the increasing need for bitumen with the increasing amount of rubber, causing the rubber to retain the binder, potentially leading to a lack of coverage on the aggregates.

Additionally, several factors, including the elements and pollutant interacting with the material, the weather conditions - the pavement being made of and high quantity of rubber and binder, it was obviously observed an influence on the material due to the ageing procedure - and the traffic have influence on the ageing of the material. Therefore, more in-depth analysis and information on the mechanisms occurring during the production and lifetime of the pavement, molecular dynamic could be explored [45]. Indeed, the pavement underwent intense UV exposure, extreme temperatures and rain exposure. In this context, low-temperature performances were studied through the use of freeze and thaw cycles coupled with traditional asphalt testing in a previous study from the authors. It has been observed than improvements must be done to propose a viable and durable solution under freeze–thaw conditions, especially regarding the loss of particles. Therefore, the degradation mechanism must be further studied and counter methods to foster cohesiveness in the mixtures and by extension the pavement, are ongoing.

Furthermore, the paved area is constructed as a hybrid path, serving both pedestrians and cyclists. Its intentional positioning at the juncture of a sidewalk, a bike lane, and a crossing lane has the potential to enhance its utilization and frequency of passage.

The visual observations suggest the need for improvement of the superficial cohesion due to the configuration of usage of this pavement. A simple binder impregnation or other similar after-treatment coatings as studied in the laboratory experiments are not sufficient and need to be coupled with the optimization at the design phase of the formulations and mix design.

Besides, maintenance of the pavement was simulated after a span of six months. Several samples were cored, and the holes were patched with the same mixture. They validated that the patching of the holes with the same rubberised and cold mixture was possible. The IAP top layer was found fully bounded to the existing base layer as illustrated Fig. 17. Furthermore, the compaction during the *in-situ* construction gives equivalent results on the stiffness and HIC of the specimen produced in the laboratory with the gyratory compactor.

4. Conclusions

Creating IAP holds promise for enhancing urban road safety, particularly for VRUs. This study explored the initial performance of a cold-processed rubber-based IAP in both lab and field settings, assessing its preliminary mechanical properties, impact reduction performances, friction qualities, and outdoor durability.

- The developed material's elasticity is demonstrated; uniaxial vertical deformation tests show it can fully compress and relax under applied stress, up to $\leq$ 5% deformation, these properties are needed for enduring loads while preserving impact-attenuation and protective characteristics and qualities.
- In the in-situ condition, the pavement was walkable and bikeable within about an hour; however, early stripping was observed after six months, presumably due to the mineral aggregate coating issues caused during the mixing phase.
- The HIC measurements indicate that a cyclist's or pedestrian's fall from a greater height could be less life-threatening. This remains consistent regardless of material compaction; however, there is a decline of the CFH with the increase of the compaction. Also, after one month path use, HIC and CFH values remain valid.
- Overall, the pavement's macrotexture is coarse, minimizing skidding risk on the IAP and after six months, BPN and roughness tests remain consistent. Specifically, applying a thin emulsion layer maintains surface roughness of the IAP, but amplify skidding on icy surfaces, while an after-treatment with aggregates and emulsion together increase the slipping risk on the IAP when the surface is icy.
- Material coring on-site confirms strong bonding to the base layer, enabling hole patching with the same rubberised cold mixture. This has significant implications for future material maintenance.

This study opens opportunities for future research to perform more in-depth analysis of the mechanisms occurring in the material, especially its aging and degradation at a microscopic and molecular scale. In parallel, another orientation will aim at substituting conventional virgin aggregates with reclaimed asphalt pavement (RAP) and adopting bio-based binders as an alternative to fossil-derived products. This strategic direction is aimed at advancing the development of environmentally sustainable pavement solutions.

CRediT authorship contribution statement

Christina Makoundou: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing. **Kenth Johansson:** Validation, Writing – review & editing. **Viveca Wallqvist:** Validation, Investigation, Writing – review & editing. **Cesare Sangiorgi:** Investigation, Validation, Resources, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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