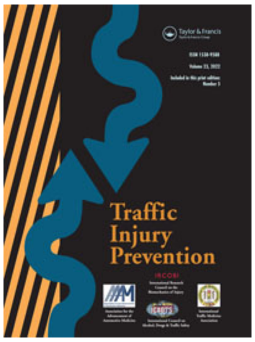

Traffic Injury Prevention

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/gcpi20

A rubberized impact absorbing pavement can reduce the head injury risk in vulnerable road users: A bicycle and a pedestrian accident case study

Pooya Sahandifar, Christina Makoundou, Madelen Fahlstedt, Cesare Sangiorgi, Kenth Johansson, Viveca Wallqvist & Svein Kleiven

TRAFFIC INJURY PREVENTION
2022, VOL. 23, NO. 5, 315–320
https://doi.org/10.1080/15389588.2022.2067990

A rubberized impact absorbing pavement can reduce the head injury risk in vulnerable road users: A bicycle and a pedestrian accident case study

Pooya Sahandifar[a], Christina Makoundou[b], Madelen Fahlstedt[a], Cesare Sangiorgi[b], Kenth Johansson[c], Viveca Wallqvist[c], and Svein Kleiven[a]

[a]Neuronic Engineering, KTH Royal Institute of Technology, Stockholm, Sweden; [b]Department of Civil, Chemical, Environmental, and Materials Engineering, University of Bologna, Bologna, Italy; [c]Department of Material and Surface Design, RISE Research Institutes of Sweden, Stockholm, Sweden

ABSTRACT

Objective: Vulnerable Road Users (VRU), including pedestrians and cyclists, are generally the least protected road users and are frequently missed in the planning process of preventive measures. Rubberized asphalt mixtures were originally developed as a possible environmentally friendly solution to recycle the End-of-Life Tires while making the pavements more durable. The objective of the current study was to explore the effects of increasing the rubber content of the common rubberized asphalt mixtures in reducing the head injuries risk for VRUs.
Method: To achieve this purpose, four different sample series with 0, 14, 28, and 33 weight percent rubber in each were tested. A compressive test without permanent deformation and one with failure were performed on each sample series. The mechanical behavior of each set was modeled using a MAT_SIMPLIFIED_RUBBER material model in LS-Dyna and validated against a standard Head Injury Criterion (HIC) drop test. Ultimately, previously low-speed accident reconstructed cases, a bicycle and a pedestrian one, were used to assess the effect of varying the rubber content on reducing the head injury risk.
Results: In the bicycle accident case, the risk of skull fracture was reduced from 0.99 to 0.29 when comparing the non-rubberized asphalt mixture with the 33% rubber mixture. In the same accident case, the risk of concussion, evaluated using the logistic regression method, was reduced from 0.97 in the non-rubberized mixture to 0.81 in the 33% rubber mixture. The initial conditions, linear and rotational velocities, were lower for the pedestrian case compared to the bicycle case (the bicycle case was more severe compared to the pedestrian case), which led to lower strains in the pedestrian case. In the pedestrian accident case, the risk of skull fracture was reduced from 1.00 in the non-rubberized mixture to 0.63 in the 33% rubber mixture, while the risk of concussion was reduced from 0.64 to 0.07.
Conclusion: The rubberized asphalt mixtures could reduce the head injury risk for the studied cases when the rubber content in the asphalt mixture increases.

ARTICLE HISTORY
Received 9 October 2021
Accepted 15 April 2022

KEYWORDS
Rubberized pavement; recycled rubber; head injury; bicycle accident; pedestrian accident; vulnerable road users

Introduction

Between 20 and 40% of the road users in European cities are cyclists or pedestrians. Among all global traffic accident deaths and injuries, VRUs (pedestrians-cyclists-motorcyclists) share half of the victims (World Health Organization (WHO)) 2018). Another published study comprising 31 cities' traffic fatalities from 2011 to 2015, of which 18 were European, suggests that the median urban traffic casualties are close to 80% for VRUs, where pedestrians and cyclists make up to 50% of those fatalities. It also states that the rate of fatality reduction is slower in cities compared to the corresponding national level. Although a possible reason for this difference is not clear, it can be speculated that VRUs do not similarly benefit from the safety and injury prevention advances in recent decades (Santacreu 2018), such as 2 + 1 roads, anti-lock braking system, collision avoidance system, electronic stability control.

Despite the burden of the vulnerability of pedestrians and cyclists even in the absence of any vehicle, the pavements used by VRUs usually follow the same design and construction criteria as the light and heavy vehicle trafficked roads. In most pavements, stiff asphalt concrete is applied as a surface layer, where the pedestrians are not protected by any means, and cyclists can be protected only against head injury if wearing a helmet. The helmet use varies largely between countries and within countries (Santacreu 2018). Helmets have shown a protective effect (Fahlstedt et al. 2016); however, more can be done in addition to personal protection, such as external/collective preventive measures,

CONTACT Pooya Sahandifar pooysaha@kth.se KTH Flemingsberg, Hälsovägen 11, SE-141 57 Huddinge, Sweden.
Associate Editor Brian D. Stemper oversaw the review of this article.
Supplemental data for this article can be accessed online at https://doi.org/10.1080/15389588.2022.2067990

like improvement of the pavement layers, which have the potential to protect more road users independent of personal protection choices.

Many studies show that using recycled waste tires, also known as End-of-Life Tire (ELT) crumb rubber, can potentially improve the performance and the environmental friendliness of asphalt mixtures for pavement layers (Dondi et al. 2014; Eskandarsefat et al. 2018; Zhang et al. 2019). It is indicated that those rubberized mixtures have better durability, performance, and recoverability compared to traditional mixtures produced without rubber (Zhang et al. 2019). Although the capability of rubber in improving the characteristics of the asphalt concretes is tested extensively, only a few studies conducted tests to evaluate the injury prevention capability of rubberized asphalt mixtures (Wallqvist et al. 2017). A previous study (Wallqvist et al. 2017) has shown that adding rubber in the asphalt mixtures could potentially reduce the head injury risk for VRUs. However, the effect of changing rubber content in the asphalt mixtures on reducing head injury has not been studied yet. Adding high quantities of rubber to the paving mixture could abate the pavement stiffness, thus reducing the risks of injuries on footpaths or foot/bike lanes (Makoundou et al. 2021). Previous studies limited the rubber content in the asphalt mixtures to prevent possible deterioration of asphalt characteristics, whereas this decision can limit the extent of the potential protective capacity of the asphalt.

The aim of the current study is to evaluate the potential effects of varying the rubber content in the rubberized asphalt concrete on reducing the risk of head injuries. Three different rubber contents of 14, 28, and 33 weight percent (%wt.), in addition to a reference asphalt mixture (0% rubber) and a playground material (100% rubber), were modeled in LS-Dyna. The developed material model for each mixture was validated using the standard Head Injury Criterion (HIC) drop test. Finally, the validated material model for each mixture was implemented in two low-speed accidents reconstructions, a bicycle (Fahlstedt et al. 2015) and a pedestrian fall (Gilchrist and Doorly 2009), to evaluate the preventive effect of varying the rubber content on the head injuries.

Methods

Three asphalt mixtures, in addition to a reference non-rubberized mixture, were developed. A compressive test without permanent deformation and one with failure was performed on each of the mixtures. These tests were used to implement the mechanical behavior of samples in LS-Dyna using the MAT_SIMPLIFIED_RUBBER material model. The developed material model for each sample was validated using the standard Head Injury Criterion (HIC) drop test. Finally, the validated material models were used to simulate both a bicycle and a pedestrian accident case. In addition to the asphalt mixtures, the two cases were also modeled using a typical playground rubber composite material.

Samples production method

The rubberized asphalt samples were produced following the same approach as detailed previously (Makoundou et al. 2021). The mixture was designed and produced following methods similar to those already used in the asphalt industry. This is the main difference between the proposed paving solution and common playgrounds surfacing. Initially, the virgin aggregates and bitumen were heated up to 160 °C and mixed until homogenization. Later, the rubber was added to the mixture to obtain each of the samples containing respectively 14, 28, and 33%wt. of rubber on the weight of the mixture. The mixing process lasted enough to have a fully coated and homogenous mixture. Finally, each group of specimens was compacted using a standard shear gyratory compactor (EN 12697-31). A reference sample was also produced with no added rubber. The standard diameters of the cylindrical samples were 100 or 150 mm (Table A1, see online supplement). The samples were color-coded for identification: the 0, 14, 28, and 33%wt. samples' surfaces were colored in orange, red, white, and green, respectively (Figure A1, see online supplement).

Mechanical testing and material modeling

The compacted asphalt samples were required to be smaller in diameter size to keep the forces below the limits of the available mechanical testing machines. Consequently, the sample was cored with a 40 mm coring rig (Figure A1, see online supplement). Two types of tests were performed on each of the mixtures: compressive test without permanent deformation and compressive test with failure (destructive test). A compressive elastic test on each sample was performed in which a 1% strain with a vertical displacement rate of 0.5 mm/min was applied. In the destructive test, samples were compressed with a vertical displacement rate of 5 mm/min until the failure point of either visible cracks in the samples or maximum absolute stress in the stress-strain curve. Both tests were performed using the Instron Universal Testing Machine Model 5567 was equipped with a 30 kN load cell. The viscoelastic parameters were neglected based on the evaluation of the 33% mixture (Appendix II). All tests were performed at room temperature (21 °C).

The constitutive behavior of the samples was modeled using a material model *MAT_SIMPLIFIED_RUBBER in LS-Dyna (LSTC 2020), and the samples were assumed to be isotropic. The destructive compression test results were directly implemented in the material card (Table A1, see online supplement).

The energy dissipation in the model during unloading was governed using a hysteresis unloading (HU) and shape factor of 0.1 and 5, respectively, for all samples. A summary of material properties can be found in Table A1, see online supplement. The stiffness of the reference sample (0% rubber) was significantly higher than the other samples. It was consequently modeled as rigid.

Validation of material model using standard HIC drop test

A standard HIC drop test, according to EN 1177:2018 + AC:2019 standard, was used to validate the material modeling of each sample that is implemented in LS-Dyna. A hemispheric 4.6 kg impactor with a diameter of 160 mm was released from different heights, and the impact speed and acceleration of the impactor were recorded (Figure A1, see online supplement). The standard suggests a sample size of at least 250 × 250 mm. Despite the recommended smallest dimensions for the asphalt samples, a cylindrical sample with 150 mm diameter for the 14% and 33% rubber content samples and 100 mm diameter for the 28% rubber content samples were used. However, impacts close to the edges were avoided to minimize the influence of edge effects. A summary of the impactor's impact speeds is reported in Table A1, see online supplement and used for the validation of the material model.

A steel spherical rigid impactor with the same diameter, weight, and impact velocity was simulated to impact the center of the cylindrical asphalt samples. The samples were assumed to be on a rigid shell representing the ground (Figure A1). The acceleration of the rigid impactor was evaluated and compared to the measured acceleration at each impact speed of the same sample. All simulations were performed using version 971 revision 10.1.0 of LS-Dyna (shared memory parallel processing (SMP)-double precision).

Bicycle accident case

The asphalt material models were implemented into a single bicycle accident reconstruction where the bicyclist had lost control and felt on the ground (Case 4, Fahlstedt et al. 2015) to evaluate the effectiveness of different rubber content of the asphalt mixture on preventing head injuries (Figure A1). A detailed finite element head model previously developed and validated against several cadaveric experiments (Kleiven 2007) was used. The initial angular and linear velocities presented by Fahlstedt et al. (2015) were applied to the head model. The head impacted each sample with 5.3 m/s ((3.42, 0.75, −4.00) in a global coordinate where Z is normal to the surface) and 4.7 rad/s resultant linear and angular velocities, respectively. The friction coefficient of 0.5 were applied to the head-ground contact according to Fahlstedt et al. (2015). It was assumed that the friction coefficient was not changed for different mixtures since the production method was the same as the regular asphalt. In addition to the head-only impact, a validated helmet model was implemented (Fahlstedt et al. 2016) to assess the combined effect of wearing a helmet and having the rubberized asphalt on head injury prevention. More details of the models can be found in previous publications (Kleiven 2007; Fahlstedt et al. 2015; 2016). In addition to the asphalt samples, a typical playground rubber-composite material was simulated as a reference to illustrate the effect of a rubber-only material (Huang and Chang 2009; Li and Kleiven 2018).

The maximum von Mises stresses of the cortical and trabecular bone were compared to evaluate the ability of the asphalt mixtures to prevent skull fractures. The skull bone was originally modeled with a plastic material model, where plasticity levels were set to 80 MPa for the cortical bone and 32.7 MPa for the trabecular bone (Fahlstedt et al. 2016). The risk of skull fracture corresponding with linear acceleration and the risk of brain concussion corresponding with principal Green-Lagrange strain were evaluated using the risk functions presented by Chan et al. (2007) and Kleiven (2007), respectively. The linear accelerations were filtered using SAE 300 filter.

Pedestrian accident case

The asphalt material models, and the playground material were also implemented into a pedestrian accident case (Gilchrist and Doorly 2009; Post et al. 2014). An elderly person tripped and fell forward onto a concrete pavement (case 3 in the study by Gilchrist and Doorly (2009)). The initial impact occurred to the head, and the fall could not be stopped with any body parts. The initial resultant linear and rotational velocities (Figure A1) of 5.35 m/s ((1.53, 0, −5.1) in a global coordinate where Z is normal to the surface), and 1.36 rad/s were implemented according to the pre-impact velocities of the center of gravity of the head (Gilchrist and Doorly 2009). Same outputs and risks were presented for this case as for the bicycle case.

Results

The peak linear acceleration of the respective impact speeds in the HIC standard tests was compared between the simulations and experiments using the linear regression analysis (Figure 1). Accordingly, the 33% and 28% mixtures were in good agreement (slope ≈ 1; $r^2 > 0.99$) with the experimental results, whereas the peak linear acceleration of the 14%

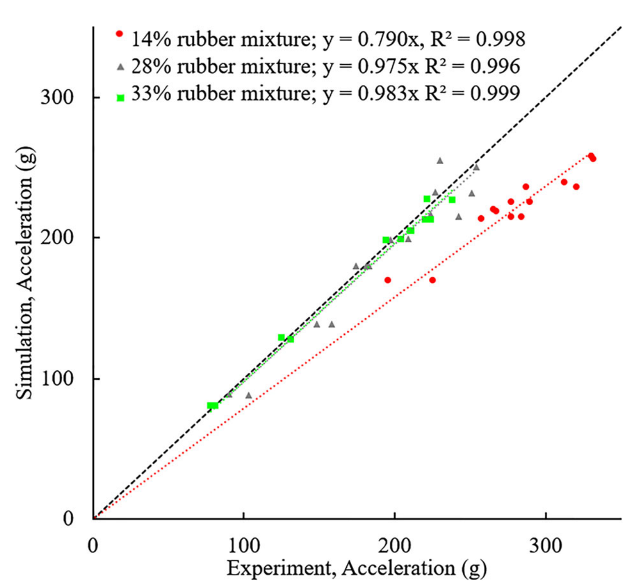

Figure 1. Linear regression analysis of maximum acceleration from the HIC drop test results and the simulation results for each asphalt sample.

Table 1. Simulation results of the pedestrian accident on different rubberized asphalt samples.

	Bicycle case				Pedestrian case			
	Peak von Mises stress for cortical bone (MPa)	Peak 1st principal Green-Lagrange strain	Risk of skull fracture based on risk curve from Chan et al. (2007)	Risk of concussion based on the risk curve from Kleiven (2007)	Peak von Mises stress for cortical bone (MPa)	Peak 1st principal Green-Lagrange strain	Risk of skull fracture based on risk curve from Chan et al. (2007)	Risk of concussion based on the risk curve from Kleiven (2007)
0% mixture-without helmet	80	0.52	0.99	0.97	80	0.31	1.00	0.64
14% mixture	80	0.52	0.98	0.97	80	0.26	1.00	0.48
28% mixture	70.7	0.45	0.77	0.92	69.6	0.13	0.96	0.14
33% mixture	24.1	0.38	0.29	0.81	39.2	0.08	0.63	0.07
Playground	17.6	0.38	0.07	0.83	29.3	0.08	0.23	0.07
0% mixture-with helmet	21.4	0.27	0.06	0.51	–	–	–	–
33% mixture-with helmet	15.9	0.29	0.04	0.57	–	–	–	–

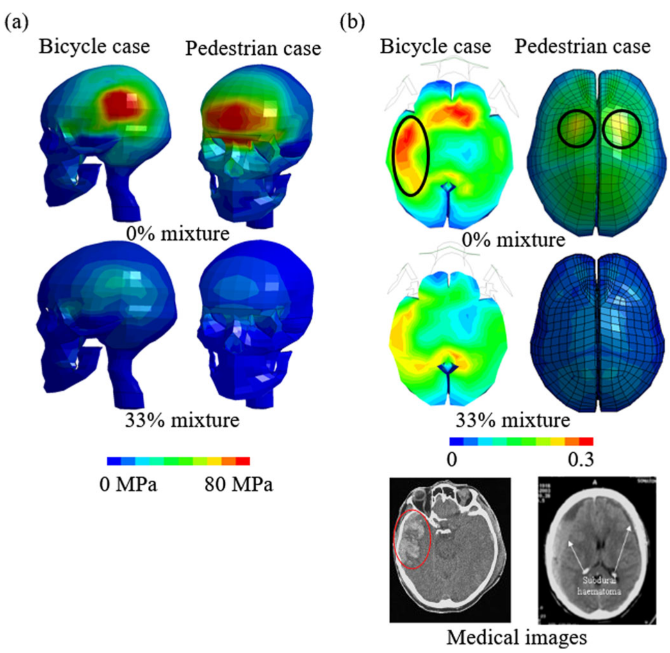

Figure 2. (a) Comparison of peak von Mises stresses (MPa) on the cortical bone between the 0% and 33% rubber contents. The level of plasticity for cortical bone was set to 80.0 MPa. The highest stresses on the skull bone occurred at the impact position for the individual case; (b) Comparison of the peak 1st principal Green-Lagrange strain on the brain tissue between 0% and 33% rubber contents. The black circles correspond to the reported medical records of head injury in the bicycle and pedestrian case. Medical image for the bicycle case is from The Accident Analysis & Prevention, Vol. 91, Madelen Fahlstedt, Peter Halldin, Svein Kleiven, The protective effect of a helmet in three bicycle accidents—A finite element study, 135–43, Copyright (2021, Licence number: 5218740986803), with permission from Elsevier; the injury region is marked with a red circle. Medical image for the pedestrian case is from "An in-depth analysis of real world fall accidents involving brain trauma." (2009), Michael D. Gilchrist and Mary C. Doorly, Copyright (CC BY-NC-ND 3.0 IE), the injury region is marked with arrows.

mixture was underestimated (slope = 0.79; $r^2 > 0.99$). The acceleration-time curves for different impact speeds on each of the asphalt mixtures are presented in Appendix III.

The 14% mixture does not effectively reduce the peak von Mises stresses (Table 1), and both bicycle and pedestrian cases reach the plastic stress level of 80.0 MPa defined in the material card. The 28% mixture reduces the stresses by approximately 11% in the cortical bone compared to the reference (0% rubber content) sample in both cases. The 33% mixture reduces the stresses on the cortical bone by 70 and 50% compared with the reference model for bicycle and pedestrian cases, respectively (Figure 2). Moreover, wearing a helmet on the 33% mixture could further reduce the stresses on the cortical bone by 25% compared with the helmets on the reference (0% rubber content) asphalt mixture.

The 1st principal strain is evaluated on the brain tissue in each sample for both bicycle and pedestrian cases (Table 1). In the bicycle case, the strain is not reduced in the 14% mixture and slightly increased (1.1%), whereas it only reduced about 13% in the 28% mixture. The 33% mixture has the most notable reduction among the asphalt samples, compared with the no-helmet case, with 27 and 75% in the bicycle and pedestrian cases, respectively (Figure 2). Although wearing a helmet when falling on the 33% mixture further reduced the stress and acceleration results, the principal strain slightly increased (6.6%).

In the bicycle case, the risk of skull fracture significantly drops up to 70% for the 33% mixture, whereas playground material can reduce it up to 90% (Table 1). The risk of concussion only reduces 16%, which is still high compared to the helmet on the reference asphalt mixture case. In the pedestrian case, the risk of skull fracture for the 33% mixture is about three times the playground material (0.63 compared to 0.23), whereas their risk of brain concussion is similar (0.07).

Discussion

It was indicated that increasing the rubber content and indirectly reducing the stiffness of the material improves the capacity of the asphalt mixtures to reduce the risk of injury. Although the softest asphalt mixture, with the highest rubber content, was not as effective as wearing a helmet, it greatly reduced the risk of skull fracture for the bicycle accident case study. Similarly, the same mixture reduced the brain strain up to 75% and reduced the von Mises stresses on the skull up to 50% for the pedestrian case.

For the bicycle accident case, the peak linear acceleration decreases as the rubber content increases in the different rubberized asphalts. Although the peak linear acceleration is reduced in all rubberized samples, the 14% mixture was not soft enough to prevent the skull fracture (Figure A5, see online supplement). The peak stress of the cortical and trabecular bone was reduced in the 28% and 33% mixtures alongside the peak linear acceleration, which could potentially indicate that increasing the rubber content above a specific threshold can reduce the skull fracture risk. It was indicated that reducing the linear acceleration can mainly reduce the risk of skull fracture, which is supported by previous findings (Chan et al. 2007; Kleiven 2013).

It is shown that a helmet is still the best preventive tool with a 48% reduction of peak principal strain and around 50% risk of brain concussion. The helmet model used in the current study is similar to the traditional helmet designs currently available on the market. Wearing those types of helmets on the asphalt mixture with 33% rubber further reduces the risk of skull fracture. However, the peak principal strain in the brain tissue increased to 0.29 (from 0.27) compared to wearing the helmet on the regular asphalt (0%). A possible explanation might be due to the increased contact area and contact time. The rubberized asphalt deforms after the impact, which increases the contact area between the helmet and the asphalt layer. Moreover, the time of contact increases due to the reduced stiffness of the material. Those two factors can change the dynamic of the head and the rotational acceleration, which indirectly correlates with the increased brain tissue strains.

In the pedestrian accident case, the peak linear acceleration of the 0% mixture was 683.2 g, which is comparable to the HIII headform experiment result (686.9 g) of a similar pedestrian accident reconstruction (Post et al. 2014). The peak linear acceleration dropped down to 67% for the 33% mixture. Despite the medical reports of no skull fracture for the pedestrian case, the peak stresses in a small number of elements have reached the limit of the cortical bone for the 14% and 0% mixtures. Even the risk of skull fracture for the 33% mixture was above 50%, which was higher than for the playground material (100% rubber).

The brain injury risk was developed using the logistic regression method. Therefore, small differences in the risk would be expected for deviations in the strain when it is closer to each end of the risk curve. The brain injury risk in the bicycle case when falling on the 0% asphalt sample was approximately 1, whereas the risk for the pedestrian case was 0.64. It means that the same relative reduction of maximum strain can cause a greater reduction in the risk of injury for the pedestrian case. The 28% asphalt mixture could merely reduce the peak principal strain up to 13%, while the 33% asphalt mixture reduced the strain up to 27% for the bicycle case. The peak principal strain and the risk of brain concussion were reduced considerably for the 33% and 28% mixtures for the pedestrian case. In addition to the nature of logistic regression curves, the initial conditions for the pedestrian case led to lower rotational velocity and linear accelerations during impact compared to the bicycle accident. It was shown (Kleiven 2007) that lower rotational kinematics leads to lower strains in the brain tissue, which contributes to the better performance of the asphalt mixtures in the pedestrian case. It suggests a potential preventive effect of the rubberized asphalt samples for pedestrian accidents.

There are some limitations in the current study. The number of different rubber contents was limited to three (14, 28, and 33%wt.), which did not allow for any practical conclusions about recommended thresholds for the minimum and maximum amount of rubber needed to ensure the preventive effects of the rubberized asphalt. Furthermore, the simulations are run without the inclusion of the neck and the rest of the body, which could influence the results. Fahlstedt et al. (2016a) showed that the influence of neck and body was affected by the impact situations on the concrete surface in a bicycle accident. In pedestrian-car accidents where the simulation duration or the impact velocities are higher compared to pedestrian or bicycle accidents, the influence of the neck muscles was shown to be more noticeable (Yu et al. 2020). Other studies have suggested that the compliance of the impact surface influences the importance of including the neck and the rest of the body. For instance, Rueda and Gilchrist (2010) concluded that the impact to the turf in jockey accidents had a long contact duration between the head and turf which motivates inclusion of the neck. The experiments were limited to two samples for each rubber content for the compression tests. This limitation can increase the influence of inhomogeneity or production defects in the modeling of mixtures. The 28% and 33% mixtures had good agreement with the experimental result, which could alleviate the concerns for this limitation; however, the 14% mixture was underestimating the experimental results (Figure 1), which could indicate that a simpler model like the elastic model could be a better material model for this mixture. Another limitation is that the drop tests were performed on smaller sample diameters than the suggested dimensions according to the standard. This size could potentially affect the resultant impact responses of the sample due to edge effects. The drop tests were not used as an indicator of the injury prevention capability of the rubberized asphalt mixtures, and it was only used for validation of the material models. Furthermore, the friction coefficient of the samples was assumed to be the same for head-to-ground contacts. Fahlstedt et al. (2016) performed a sensitivity analysis for the friction coefficient (±0.2) and demonstrated that the peak strain responses change approximately ±0.07 in head-to-ground contacts. Moreover, the asphalt mixtures were produced similar to non-rubberized mixtures, and the surface was not specifically treated to affect the friction. This supports the similar friction coefficient assumption for the asphalt mixtures. Ultimately, the samples were assumed to be isotropic and nearly incompressible due to the presence of rubber. The bulk modulus of the samples was indirectly calculated using Young's modulus and Poisson's ratio. Despite the above limitations, it was indicated that the rubberized asphalt mixtures could potentially reduce the head injury risk when the rubber content increases.

Among the three rubber contents tested, the softest asphalt mixture containing 33%wt. rubber reduced the risk of skull injury and brain tissue injury in the bicycle accident by 70 and 16%. The risk of brain concussion reduced most in the pedestrian case, where it was lowered to 7% with the 33% rubberized asphalt mixture. Given that only one pedestrian and one cyclist head impact cases were studied, and these types of impacts can vary greatly in real-world accidents, it is still necessary to further investigate the minimum rubber content that is required to minimize the risk of any head injuries. Ongoing research is addressing the improvement of material workability and durability by means of alternative binders and rubber surface treatment. In parallel, reduced severity in case of human impact and mitigation of the environmental footprint are considered in the development of the impact-absorbing pavements.

Acknowledgment

Authors are grateful to the suppliers of the recycled crumb rubber (Ragn-sells through SDAB, Sweden) and bitumen used in this project.

Funding

This work was supported by "BVFF – Bana väg för framtiden" under Grant number 2016-02; Sweden's innovation agency, Vinnova under Grant number: D.nr.: 2013-04465); the SAFERUP! Project through the European Union's Horizon 2020 Research and Innovation program Marie Skłodowska-Curie under Grant number 765057.

ORCID

Pooya Sahandifar http://orcid.org/0000-0001-6923-4751
Christina Makoundou http://orcid.org/0000-0003-1565-1554
Madelen Fahlstedt http://orcid.org/0000-0002-0980-4051
Cesare Sangiorgi http://orcid.org/0000-0003-1006-5935
Kenth Johansson http://orcid.org/0000-0003-2008-1832
Viveca Wallqvist http://orcid.org/0000-0003-1634-6789
Svein Kleiven http://orcid.org/0000-0003-0125-0784

References

Chan P, Diego S, Rigby P, Takhounts E, Zhang J. 2007. Development of a generalized linear skull fracture criterion (June 2015).

Dondi G, Tataranni P, Pettinari M, Sangiorgi C, Simone A, Vignali V. 2014. Crumb Rubber in cold recycled bituminous mixes: Comparison between traditional crumb rubber and cryogenic crumb rubber. Constr Build Mater. 68:370–375. doi:10.1016/j.conbuildmat.2014.06.093

Eskandarsefat S, Sangiorgi C, Dondi G, Lamperti R. 2018. Recycling asphalt pavement and tire rubber: A full laboratory and field scale study. Constr Build Mater. 176:283–294. doi:10.1016/j.conbuildmat.2018.05.031

Fahlstedt M, Depreitere B, Halldin P, Vander Sloten J, Kleiven S. 2015. Correlation between injury pattern and finite element analysis in biomechanical reconstructions of traumatic brain injuries. J Biomech. 48(7):1331–1335. doi:10.1016/j.jbiomech.2015.02.057

Fahlstedt M, Halldin P, Alvarez VS, Kleiven S. 2016. Influence of the body and neck on head kinematics and brain injury risk in bicycle accident situations. In: IRCOBI Conf 2016. Malaga (Spain); p. 459–478.

Fahlstedt M, Halldin P, Kleiven S. 2016. The protective effect of a helmet in three bicycle accidents – A finite element study. Accid Anal Prev. 91:135–143. doi:10.1016/j.aap.2016.02.025

Gilchrist MD, Doorly MC. 2009. An in-depth analysis of real world fall accidents involving brain trauma. In: Gefen A, editor. The Pathomechanics of tissue injury and disease and the mechanophysiology of healing. [place unknown]: Research Signpost.

Huang TJ, Chang LT. 2009. Design and evaluation of shock-absorbing rubber tile for playground safety. Mater Des. 30(9):3819–3823. doi:10.1016/j.matdes.2008.12.024

Kleiven S. 2007. Predictors for Traumatic Brain Injuries Evaluated through Accident Reconstructions. In: SAE Technical Paper. Vol. 2007–October. [place unknown]: SAE International; [accessed 2020 Nov 18]. https://www.sae.org/content/2007-22-0003/

Kleiven S. 2013. Why most traumatic brain injuries are not caused by linear acceleration but skull fractures are. Front Bioeng Biotechnol. 1:15. http://journal.frontiersin.org/article/103389/fbioe.2013.00015/abstract

Li X, Kleiven S. 2018. Improved safety standards are needed to better protect younger children at playgrounds. Sci Rep. 8(1):1–12. doi:10.1038/s41598-018-33393-z

LSTC. 2020. LS-DYNA R12 keywords manual, version 971. [place unknown]: Livermore Software Technology (LST), An Ansys Company; [accessed 2021 Jan 6]. www.lstc.com

Makoundou C, Sangiorgi C, Johansson K, Wallqvist V. 2021. Development of functional rubber-based impact-absorbing pavements for cyclist and pedestrian injury reduction. Sustainability. 13(20):11283. https://www.mdpi.com/2071-1050/13/20/11283/htm doi:10.3390/su132011283

Post A, Hoshizaki TB, Gilchrist MD. 2014. Comparison of MADYMO and physical models for brain injury reconstruction. Int J Crashworthiness. 19(3):301–310. http://www.tandfonline.com/doi/abs/101080/13588265.2014.897413 doi:10.1080/13588265.2014.897413

Rueda MAF, Gilchrist MD. 2010. Equestrian helmet design: A computational and head impact biomechanics simulation approach. In: IFMBE Proceedings. Vol. 31 IFMBE. Berlin : Springer, Berlin, Heidelberg; p. 205–208. [accessed 2021 Jan 14]; www.springerlink.com

Santacreu A. 2018. Safer city streets global benchmarking for urban road safety. Paris. [accessed 2020 Nov 10]. https://www.itf-oecd.org/safer-city-streets-global-benchmarking-urban-road-safety

Wallqvist V, Kjell G, Cupina E, Kraft L, Deck C, Willinger R. 2017. New functional pavements for pedestrians and cyclists. Accid Anal Prev. 105:52–63. doi:10.1016/j.aap.2016.04.032

World Health Organization (WHO). 2018. Global Status report on road safety 2018: Summary. Geneva; [accessed 2021 Jan 5]. http://apps.who.int/bookorders.

Yu C, Wang F, Wang B, Li G, Li F. 2020. A Computational biomechanics human body model coupling finite element and multibody segments for assessment of head/brain injuries in car-to-pedestrian collisions. Int J Environ Res Public Heal. 17(2):492. https://www.mdpi.com/1660-4601/17/2/492/htm doi:10.3390/ijerph17020492

Zhang B, Chen H, Zhang H, Kuang D, Wu J, Zhang X. 2019. A study on physical and rheological properties of rubberized bitumen modified by different methods. Materials (Basel). 12(21):1–14. doi:10.3390/ma12213538