Head protection performance of impact-absorbing pavement under oblique impacts

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I. INTRODUCTION

Traumatic brain injury (TBI) is a growing public health concern worldwide. While vehicle-related accidents have decreased in Sweden, morbidity and mortality among vulnerable road users (VRUs) continue to rise [1]. Head injuries often lead to permanent impairments, and approximately 27,000 pedestrians annually require emergency care after falls in traffic environments [2]. Given the increasing popularity of alternative transportation modes, there is an urgent need for effective strategies to prevent TBI in VRUs.

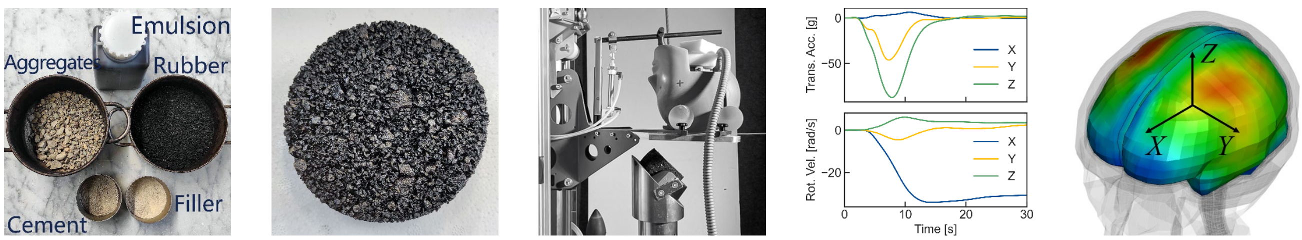
Currently, most road surfaces consist of conventional stiff asphalt, providing little protection and leaving VRUs dependent on personal protective equipment, such as helmets [3]. Inspired by playground surfaces, impact-absorbing pavement (IAP) is being developed in which a portion of the mineral aggregates is replaced with rubber granules derived from recycled car tyres [4]. Asphalt-based pavement in early investigation was assessed during direct impact, as real-world head impacts typically occur at oblique angles [5]. This study aims to address this gap by biomechanically evaluating IAP through oblique impacts to analyse its head protection performance, thus providing new insights toward safer traffic environments for VRUs.

II. METHODS

Rubberised asphalt material: the IAP containing 56% rubber by volume was evaluated for head protection performance. To reach this percentage, fine mineral aggregates are substituted with similarly sized recycled rubber granules, using a Hot-Rolled Asphalt sieving curve as a reference [6]. The final mixture includes 22% aggregates and fillers, 56% rubber, 21% SBS polymer-modified bitumen-based emulsion, and 1% cement additive, mixed for homogeneity (Fig. 1(a)). Samples of 100 mm diameter and 46 mm thickness (Fig. 1(b)) were compacted at room temperature using gyratory compaction (30 and 80 cycles). Some samples were also artificially aged.

Oblique impacts setup: oblique impact tests were conducted at the helmet lab at KTH using a Hybrid III headform dropped onto IAP samples fixed on the angled anvil (45°) (Fig. 1(c)). Three impact locations (Xrot, Yrot, Zrot) and two drop heights (150 cm, 5.4 m/s and 205 cm, 6.0 m/s) were employed. Each configuration was tested twice, and headform kinematics were recorded using a 3-2-2-2 accelerometer array at 25 kHz. A total of 30 impacts were performed on five IAP samples at three impact locations.

Data analysis: the experimental kinematics (Fig. 1(d)) were imposed on the KTH head model to analyse the brain response (Fig. 1(e)). Fifteen FE simulations were performed in LS-DYNA for five IAP samples at three impact locations. All simulations lasted 30 ms. Eight head injury metrics (including Peak Linear Acceleration (PLA), Peak Angular Velocity (PAV), Peak Angular Acceleration (PAA), Head Injury Criterion (HIC), Brain Injury Criterion (BrIC), Diffuse Axonal Multi-Axis General Evaluation (DAMAGE), Maximum Principal Strain (MPS) and Maximum Tract-Oriented Normal strain (MTON) [7]) were used to evaluate the brain response during oblique impacts. Moreover, the head injury metrics of IAP at 6.0 m/s were also compared with those of helmets from a previous study [8].



(a) IAP components. (b) IAP samples. (c) Oblique impacts. (d) Head kinematics. (e) FE simulations.

Fig. 1. Illustration of methodology. (a) Components of IAP. (b) The IAP sample after cycling. (c) Oblique impact tests using Hybrid III headform. (d) Headform kinematics in three directions. (e) The FE model for injury analysis.

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III. INITIAL FINDINGS

Oblique impacts against IAPs at three impact locations (Xrot, Yrot, and Zrot), strain distribution, head injury metrics of IAP, and helmet comparison are shown in Fig. 2, Fig. 3, Table I, and Fig. 4, respectively. All injury metrics except for MPS and MTON are derived from the kinematics. For example, the PLA across all impact cases averaged 114.89 ± 17.68 g; HIC was 424.96 ± 146.44. At the brain tissue level, MPS was 0.34 ± 0.03.

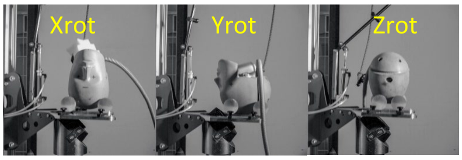

Fig. 2. Headform oblique impacts against IAP at Xrot, Yrot, and Zrot, respectively.

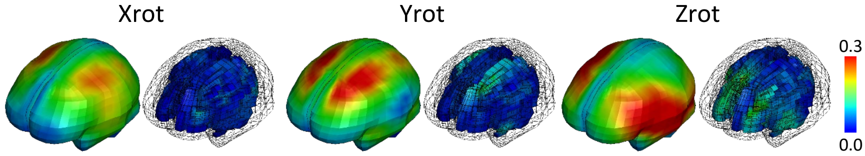

Fig. 3. MPS distribution (left) of brain tissue and MTON distribution (right) of white matter during oblique impact at 6.0 m/s at three impact locations.

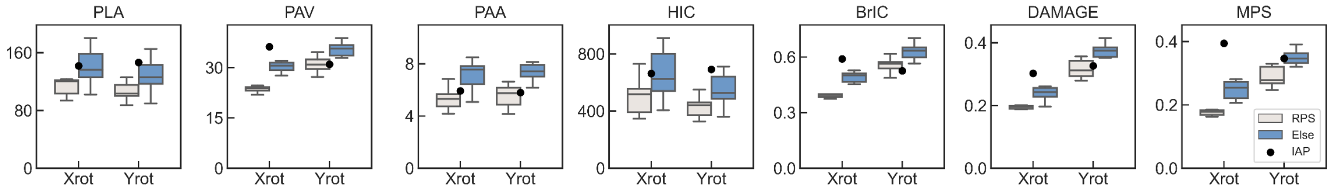

Fig. 4. Comparison of head injury metrics in oblique impacts at 6.0 m/s between IAP and helmets [8], where RPS represents helmets with rotational protection system, and Else represents helmets without rotational protection system.

TABLE I
SUMMARY OF HEAD INJURY METRICS OF ALL IAPS IN THE FORM OF MEAN ± STANDARD DEVIATION AT THREE IMPACT LOCATIONS (XROT, YROT, AND ZROT) AND TWO DROP HEIGHTS (150 CM AND 205 CM)

	PLA [g]	PAV [rad/s]	PAA [krad/s^2]	HIC	BrIC	DAMAGE	MPS	MTON
Xrot	108.60 ± 19.51	34.45 ± 1.12	5.66 ± 0.34	386.84 ± 158.12	0.55 ± 0.02	0.28 ± 0.01	0.35 ± 0.01	0.23 ± 0.01
Yrot	115.63 ± 17.84	28.83 ± 1.23	4.97 ± 0.53	423.38 ± 151.67	0.49 ± 0.02	0.30 ± 0.02	0.31 ± 0.02	0.23 ± 0.02
Zrot	120.44 ± 17.51	31.83 ± 2.51	5.15 ± 0.73	464.67 ± 152.49	0.68 ± 0.06	0.40 ± 0.04	0.35 ± 0.04	0.28 ± 0.04

IV. DISCUSSION

This study biomechanically evaluated the head protection performance of the IAP through oblique impacts. Overall, the IAP demonstrated head protection performance comparable to helmets during 6.0 m/s oblique impacts (Fig. 4). Helmets with rotational protection system (RPS) showed lower values across all injury metrics compared to others. For linear-based metrics (e.g. PLA and HIC), IAP values were slightly higher than the median of non-RPS helmets. For rotational metrics (e.g. PAV and PAA), IAP values were even lower than the median of non-RPS helmets in Yrot. Injury metrics in Zrot are not comparable because of the different impact location. However, since helmet and IAP data were obtained under different laboratory conditions, further study is needed.

The use of recycled tyre rubber in IAP not only promotes the recycling of end-of-life materials but also contributes to enhancing the safety of urban roadways. While helmets are designed to reduce the severity of head injuries, pavement characteristics can also play a role in impact absorption. Pavement, as a collective form of protection, can benefit all users. Although the combination of IAP and helmet use holds significant potential for enhancing head protection, further research is needed to better understand the VRU injury outcomes.

V. ACKNOWLEDGEMENTS

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