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Assessing Heat Stress in Industrial Helmets: A Comparative Study of Various Energy Absorbing Materials

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ABSTRACT

Heat stress is becoming an increasingly critical topic within occupational personal protective equipment. The aim of this study was to investigate the influence of impact absorption materials of industrial helmets on heat stress. Temperature and humidity build up underneath five industrial helmets was measured twice for one hour using a sweating thermal head form set to 37°C and constant water vapour emission in controlled ambient conditions. The heat index, a measure for the perceived temperature influenced by temperature and humidity, was calculated for the steady phase. The three helmets featuring expanded polystyrene (EPS) as impact absorbing material developed a microclimate with a heat index of 35.17 ± 0.72°C, 34.96 ± 0.79°C and 34.96 ± 0.99°C, while helmets featuring KOROYD as the impact absorbing material showed values of 29.10 ± 0.28°C and 30.45 ± 1.13°C. The decrease in heat index and therefore reduced heat stress could be a result of less insulative properties due to the open-cell structure of the material in the helmets with KOROYD integration.

Keywords: Heat Stress; Heat Index; Industrial Helmets; Energy Absorbing Material

INTRODUCTION

Human thermoregulation aims to keep deep body temperature within a range of ± 1°C of 37°C in order to maintain healthy body function [1]. In hot conditions, a decrease in body temperature is achieved mainly through evaporation of sweat [2]. Heat stress is a state that occurs when the body is unable to cool itself effectively [3]. This can happen in hot and humid environments, or when wearing protective clothing and/or equipment that restrict heat loss [4, 5].

Perceived temperature can be very different from the actual temperature, depending on the correlation between temperature and humidity. This is because the effectiveness of sweat evaporating to reduce body temperature decreases as humidity increases [6]. Therefore, the level of heat stress the body is exposed to increases with increasing temperature but also with increasing humidity. A common indicator to describe heat stress is the heat index (HI). It uses equation 1 to link the combined effect of temperature and humidity on the human body into a scale of perceived temperature [7, 8].

$$HI = c_1 + c_2T + c_3R + c_4TR + c_5T^2 + c_6R^2 + c_7T^2R + c_8TR^2 + c_9T^2R^2$$

Equation 1: Heat index formula

Depending on the unit of temperature, the heat index is calculated in a different set of coefficients c_{1-9} for equation 1, shown in table 1 below:

Table 1: Coefficients value for the heat index formula

	Value for HI in °F	Value for HI in °C
c_1	- 42.379	- 8.78469475556
c_2	2.04901523	1.61139411
c_3	10.14333127	2.33854883889
c_4	- 0.22475541	- 0.14611605
c_5	$- 6.83783\times10^{-3}$	- 0.012308094
c_6	$- 5.481717\times10^{-2}$	- 0.0164248277778
c_7	1.22874×10^{-3}	2.211732×10^{-3}
c_8	8.5282×10^{-4}	7.2546×10^{-4}
c_9	-1.99×10^{-6}	$- 3.582\times10^{-6}$

Heat stress is a significant problem in industrial occupational settings, where workers may be exposed to hot environments for extended periods of time. Heat stress can increase the risk of accidents [9], decrease cognitive performance [10] as well as increase unsafe work behaviour [11]. In the United States, an average of 658 heat-related deaths occur each year [12], and 436 work-related deaths due to environmental heat exposure occurred between 2011 and 2021 [13].

In addition to environmental conditions, the type of clothing and equipment worn can also have an influence on the heat stress [14]. Any type of clothing or equipment that hinders evaporation of sweat, or has an insulating effect, creates a distinct microclimate with temperatures and humidity differing from ambient conditions, which can compromise thermoregulation and increase heat stress [4, 5]. Wearing a safety helmet restricts air circulation around the head, trapping hot and humid air, which makes it more difficult for the body to cool itself [15, 16].

The aim of this study is to compare the microclimate buildup of different industrial helmets to build an understanding around which type of helmet impact absorbers are less likely to contribute to heat stress, and to develop recommendations for the design of helmets that reduce heat stress.

METHODS AND MATERIALS

Test setup

The tests were conducted in a controlled climate chamber with a maintained temperature of 21°C and 50% relative humidity. A sweating thermal head form ("Sweator Head", Inside Climate, Holzkirchen, Germany) at a constant temperature of 37°C and constant emission of water vapour was used.

Figure 1: Sweator Head lab equipment

Fourteen sensors were placed onto the head form underneath the helmet in an evenly spaced matrix to measure temperature and relative humidity. Measurements were taken every 5 seconds for one hour per test run. Two runs were recorded for each helmet on two consecutive days, reversing the order of testing on the second day to evaluate measurement repeatability. This test setup (as seen in figure 2) is designed to produce a comparable, reproducible and steady microclimate inside the helmets compared to testing on human subjects.

Figure 2: Laboratory test setup of the Sweator Head

Materials/Samples

Five industrial helmets were tested for this study, the aim being to evaluate the thermal comfort based on the internals of the helmets. All the helmets were non-vented white helmets in order to remove the variability and influence of the colour, the size, quantity, shape and positioning of any vent holes in the helmet shell.

Three helmets featured a traditional expanded polystyrene (EPS) as energy absorbing material. The remaining two helmets had an alternative energy absorption system made of an open-cell energy absorbing material: KOROYD.

All the samples were conditioned inside the climate chamber at 21°C and 50% relative humidity for at least 24 hours before testing.

The internals of the helmets tested can be seen in figures 3 and 4 below. The EPS helmets tested were from three different brands with different EPS designs. The samples were partly disassembled for the images showing the EPS or KOROYD energy absorbing materials. However, all helmets were tested fully assembled.

Helmets with EPS tested

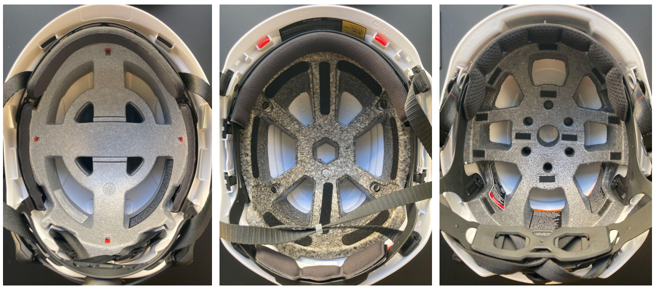

Figure 3: Helmets A, B and C (left to right). Helmet A is certified ANSI Z89.1-2014 type I, Helmets B and C are certified ANSI Z89.1-2014 type II.

Helmets with KOROYD tested

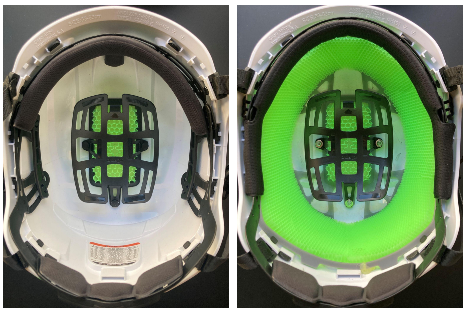

Figure 4: Helmets D (left) and E (right). Helmet D is certified ANSI Z89.1-2014 type I, Helmet E is a prototype of a ANSI Z89.1-2014 type II helmet

All the helmets tested were finished products with the exception of the helmet E with KOROYD for which a prototype was tested. This prototype was made using the same components as the helmet D with a KOROYD retention cage prototyped through 3D printing techniques.

Different types of helmet protection were tested. Helmets A and D provide crown protection according to the ANSI Z89.1-2014 type I standard. These helmets are referred to as type I helmets. Helmets B, C and E provide crown and off crown protection according to ANSI Z89.1-2014 type II standard. These helmets are referred to as type II helmets.

<u>Data Treatment</u>
The mean temperature and humidity over time of the 14 sensors is determined. As the microclimate reaches a steady state 15 minutes after the helmet is put onto the head form, the data is trimmed at that point of time. The mean temperature and humidity over the course of the stable phase of the individual test runs is taken and the heat index calculated using equation 1.

RESULTS

The following graph (Figure 5) shows the heat index development over the course of the test run. The heat index was calculated for each of the 14 sensors and an average over time was calculated for the whole experiment period of time (1h).

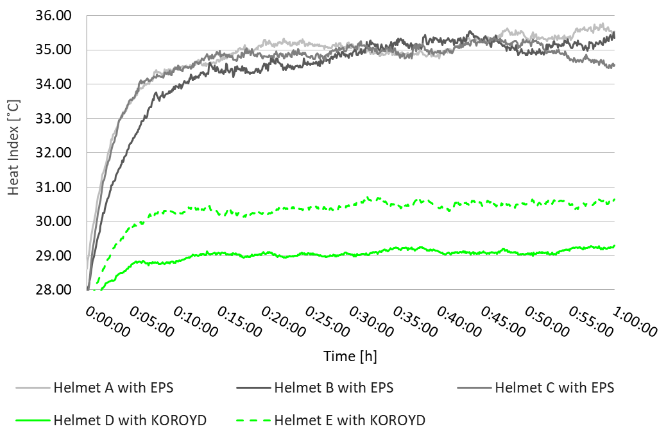

Figure 5: Heat index average over a 1h period of time for the 2 test rounds of each helmets tested

Fifteen minutes after the beginning of the test, the heat index reached a plateau which remained constant until the end of the test. For the results, analysis of only the second phase once the heat index remains stable is considered.

The helmets were sorted by the protection they provide in order to get a fair comparison. The helmets providing crown protection (ANSI Z89.1-2014 type I) achieved the following results. Helmet A with EPS showed a mean heat index of 35.17 ± 0.72°C. Helmet D with KOROYD showed a mean heat index of 29.10 ± 0.28°C. The individual results for each round can be found in the following table 2, the mean heat indices are shown in figure 6:

Table 2: ANSI Z89.1-2014 type I helmets heat index average

	Heat index [°C]		
Helmet #	1st run	2nd run	Average
Helmet A with EPS	34.66	35.24	35.17
Helmet D with KOROYD	29.29	28.90	29.10

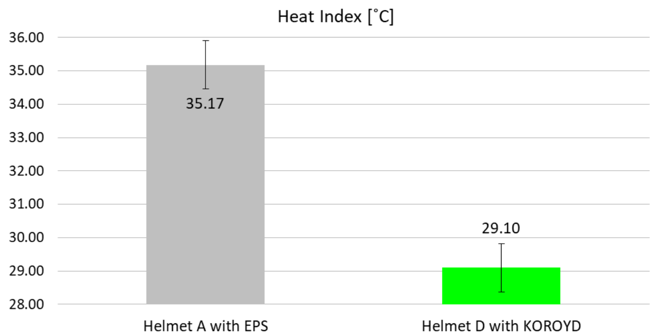

Figure 6: Heat index average from 15 min after the start to the end of the test for ANSI Z89.1-2014 type I helmets

The helmet D with KOROYD showed a significantly lower heat index. When compared to the helmet A with EPS the helmet D with KOROYD showed a reduction of 6.07°C.

The type II helmets achieved the following results. Helmet B and C with EPS showed respectively a mean heat index of 34.96 ± 0.99°C and 34.96 ± 0.79°C. Helmet E with KOROYD showed a mean heat index of 30.45 ± 1.13°C. The individual results for each round can be found in the following table 3, the mean heat indices are shown in figure 7:

Table 3: ANSI Z89.1-2014 type II helmets heat index average

	Heat index [°C]		
Helmet #	1st run	2nd run	Average
Helmet B with EPS	35.52	34.40	34.96
Helmet C with EPS	34.26	35.65	34.96
Helmet E with KOROYD	31.25	29.66	30.45

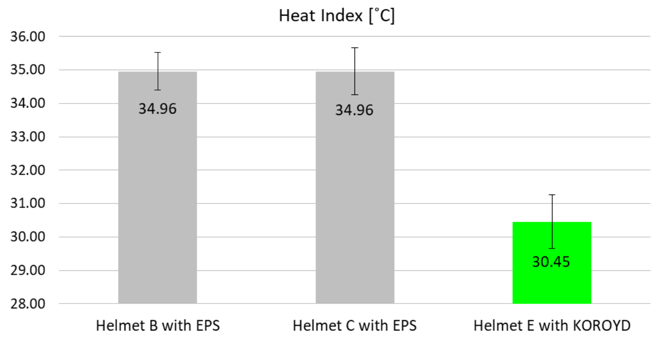

Figure 7: Heat index average from 15 min after the start to the end of the test for ANSI Z89.1-2014 type II helmets

The Helmet E with KOROYD showed a significantly lower heat index. When compared to the helmets B and C with EPS the helmet E with KOROYD showed a reduction of 4.51°C.

DISCUSSION

All the helmets featuring EPS as the energy absorber showed heat indices in the same range although the helmets tested were from different brands and had different liner geometries (shape, coverage, volume, material density). The mean heat index achieved by each helmet is shown by the following graph (figure 8):

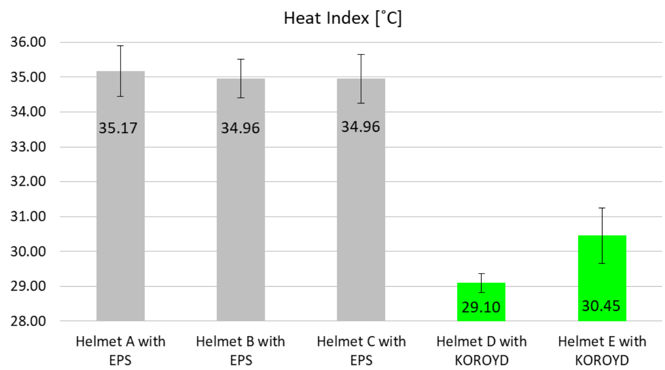

Figure 8: Heat index average from 15 min after the start to the end of the test for all 5 helmets

The insulating material characteristics of the EPS foam as well as its closed cell structure is thought to be the main factor explaining the higher heat indices.

The helmets with KOROYD performed with significantly lower heat indices for both type I and type II helmets. Considering the reduction of temperature perceived for both protection types tested, the improvement is likely linked to less insulative properties thanks to the open-cell structure of the KOROYD material.

Based on the 4.5°C and 6.0°C heat index reduction for Type II and Type I helmets respectively using KOROYD as energy absorbing material compared to using EPS seen in this study, replacing the EPS energy absorber by an open cell KOROYD system should lead to a significant heat index reduction.

This study was conducted using finished products, therefore the helmet designs are different including the energy absorbers. This experiment aimed to remove most of the parameters to evaluate the energy absorbers' performance including choosing helmets which are the same style, same colour, non-vented and passing the same standard. However, the shell material and thickness can be different from one helmet to another as well as the headband and other components. Despite this variability the helmets with EPS showed heat indices in the same range which supports the hypothesis that the heat index reduction for the helmets with KOROYD would be linked to the KOROYD material as the different designs tested showed similar performances. Further testing could prioritise a larger number of helmets to further review the influence of different designs thus informing the development of future helmets to prevent the risk of accidents due to heat stress.

CONFLICT OF INTEREST

The authors of this technical paper are either employees or are affiliated in some part with KOROYD Sarl, a company specialising in the development and manufacturing of technologies for helmets aimed at addressing heat stress concerns in occupational settings. As such, the authors acknowledge the potential for a conflict of interest that may arise from their affiliations with the aforementioned company.

To mitigate any potential bias, the study was conducted with strict adherence to scientific principles, standard protocols, and best practices within the field. Throughout the research process, measures have been taken to ensure transparency and accuracy in reporting the findings. The authors are committed to providing an objective assessment of the effectiveness of different types of industrial helmets in reducing heat stress on the human body.

Readers are encouraged to critically evaluate the information presented in this paper and consider the authors' affiliations when interpreting the results. The authors disclose their association with KOROYD and affirm their dedication to upholding the highest standards of scientific integrity and impartiality in the pursuit of knowledge and understanding related to industrial helmets and heat stress management.

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