DESIGN OF INNOVATIVE PROTECTIVE INSOLES: A HYBRID COMPONENT FOR SAFETY FOOTWEAR

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Abstract: *The use of Personal Protective Equipment (PPE) has become a necessity in view of the number of accidents at work that occurred in the past years. The European Community (EU) and the member states are creating strategies aiming the increase of the use of PPE's and consequently the decrease of the number of the accidents at work, decreasing also the number of injuries caused by them and their severity. In this paper, a brief review of safety footwear and its components will be presented focusing on penetration resistant inserts. Additionally, we present a project in development at University of Minho that aims to improve the existent shoes. This project aims the development of a new and innovative methodology for design a surface of a penetration resitant insert based in the anthropometry and biomechanical analysis of the foot. This methodology allows the design of a penetration resistant insert more comfortable and appellative than the already existent.*
Keywords: *Personal Protective Equipments, Safety Footwear, Penetration Resistant Inserts, Air permebility, thermal properties.*

1. Introduction

Every year in EU about 3 million workers were victims of accidents at work of which results 500 deaths and an absence from work of approximately three days. Due to these facts, the EU and the member states are creating strategies aiming the increase of the use of PPE and consequently the decreasing of the number of accidents at work [1].
The safety shoe industry has suffered improvements in order to increase the level of the user's comfort and decrease the manufacturing costs of the safety shoes and it´s components. Despite of this fact, nowadays, a large number of employees still neglect the use of this kind of protection. Goldcher and Acker were able to present some reasons for this [2]:

- Uncomfortable at work;
- Excessive weight, which lead to muscle fatigue at the end of the day (heel pain, calf pain);
- Lack of flexibility due to the reinforcement of the base;
- Models unsuited to the morphology of some feet;
- Occurrence of foot injuries, in part secondary to the previous two complaints: redness, blistering, hyperkeratosis, among others ;
- Lack of aesthetic and ergonomics;
- Inadequate ventilation which promote sweating, maceration and fungal infection.

According to the legislation, protective footwear can be defined as footwear including protective structures (toecaps and penetration resistant inserts) to protect the user from injuries which could arise through accidents. There are three types of protective footwear classified according to the protection that they offer: as safety shoes, protection shoes and occupational shoes. The main difference between safety, protective and occupational shoes is the toecap protection. In the case of safety shoes, toecaps must resist to a mechanical impact of 200 J, while the impact supported by the protective shoes should be 100 J. In the case of the occupational shoes, the toecap protection is not required.
The penetration resistant inserts are one of the most important components of the safety shoes and its main goal is to prevent the penetration of sharp objects. This component suffered a big evolution in the last years. Nowadays, there are mainly available two types of resistant penetration inserts, metallic or made of aramid fibers. The first ones have a thickness of ≈0.5 mm and due to their low cost production are the most used by the safety shoes producers. The ones made of aramid fiber are very flexible, making the shoe more comfortable, however, their cost is superior to the metallic inserts.
Some inserts were patented: In 1991, Kenji Okayasu [3], developed a new penetration resistant insert aiming to improve the flexibility of the existent inserts. Okayasu used small metal plates joined together allowing the insert to bend in the front part, the metal plates are involved in an involcro from plastic or rubber in order to prevent the insert damaging in the sole of the shoe. The main disadvantages of this insert are it complex manufacture process and the fact that it flexibility inflict restrictions in the movement of the foot. In 1994, Albertus Aleven [4], developed a insert composed by four layers. This insert had give for the first time stiffness and flexibility in different parts of the insert. The first layer is a polymeric protector layer with a specific protector zone of stainless steel in the front part of the insert. The joint between this two layers is

the area where the foot will bend while walking, allowing the caused tension to be absorved by the polymeric layer. The insert has a upper layer made of a fabric with anti-funghi properties and a bottom layer made of polyesther. The variation of the thickness throughout the insert area allows the optimization of the flexibility in the required areas. The disadvantage of this type of insert is it complex and expensive manufacture process, additionally, with the use of the shoes, the metallic and the polymeric layers can be separated leaving an area of the foot vulnerable to sharp objects. In 1999, Frederick Harrison [5] developed a polymeric penetration resistant insert that has a toecap and a special area to protect the heel. The main advantage of this insert is the fact that in the manufacture process of the shoe, the steps of the assemble of the toecap is eliminated once this component is already a part of the insert. This insert is made of a polymer capable of absorb a great amount of energy and comfer a good flexibility. A metallic plate is assembled in the polymer in order to improve the protection level of the insert, however, this metallic plate comfer to much stiffness to the insert. In 2003, Luigi Bettaglia [6], presented an improvement of the simple metallic inserts by applying longitudinal ribs in the back part of the insert. These longitudinal ribs form grooved ribs on the upper surface of the sole that are going to stiffen the area of the arch of the foot. In 2008, Leo Sartor and his collegues [7] developed a insert with two distinct parts. The front part of the insert is comprised of multiple layers of aramide fiber conferring a good flexibility. The back part of the insert is made of a composite material and acts like a structural element and prevents the heel torsion and therefore heel injuries. The disadvantage of this insert is the complex manufacture process.
The present work aims the development of a new and innovative penetration resistant insert for safety shoes, regarding the standards, with an improved behavior than the ones already available in the market. For that, we are trying to develop a penetration resistant insert using new and innovative materials that are not being applied in safety footwear. Aiming to improve the comfort of safety footwear, we pretend a decrease of thickness and weight, without sacrificing the physical protection offered by the same. With the decreasing of the insert weight, the shoe weight will also decrease. Another goal is to implement a high level of comfort on the penetration resistant insert aiming to the whole shoe to be more comfortable and usable to the employees. Moreover, we are considering the incorporation of comfort components on the penetration resistant insert.

2. Materials and methods

2.1 Materials

The materials selected for this work are based in polypropylene (A), on ultra high molecular weight polyethylene (UHMWPE) (B, C, D) and on aramid fibre (E, F, G, H, I, J, K). The UHMWPE based materials B and C are made by the same manufacturer, the main difference between them is their weight. The material based on aramid fibres K is from a different mannufacturer than the materials E, F, G, H, I and J. The difference between material E, and the other materials of the same manufacturer is the number of layers.

2.2 Methods

2.2.1 Penetration resistance test

The penetration resistant inserts are footwear components placed in the sole complex in order to provide protection against mechanical penetration. The penetration resistance tests were performed according to the standard EN ISO 12568 - “Foot and leg protectors - Requirements and test methods for toecaps and penetration resistant inserts”. When tested accorded to the mentioned standard, using a force of at least 1 100 N, the tip of the test nail shall not penetrate through the test piece. A "pass" result requires that the tip of the test nail does not protrude from the rear side of the test piece to be checked by visual, cinematographic or electrical detection.

2.2.2 Air permeability

The air permeability is the ability of a fabric to be crossed by the air through the pores or interstice which rate depends mainly on the size and distribution of pores or interstices between the fibres. The air permeability is determined by measuring the velocity of air flow perpendicularly crosses a specimen under specified conditions, (area and pressure). In this work the test has been performed with an area of 20 cm^2 and a pressure of 200 Pa for non-woven materials and 100 Pa for woven materials. The air permeability test has been carried out following the standard NP EN 9237-1997 – “Determination of the air permeability of textiles.“ with the air permeability tester TEXTEST FX 3300.

2.2.3 Thermal properties

The thermal properties were measured in the Alambeta. This device makes an objective assessment of thermal feeling. The Alambeta measures the thermal absorption capacity and simultaneously evaluates the stationary thermal properties such as resistance and conductivity and the dynamic properties such as thermal diffusivity and thermal absorption.
The apparatus consists of a metal block with constant temperature (30°C) which differs from sample temperature (20ºC). When the measurement begins, the measurement head touch the lower sample surface to be measured, which is located at the base of the apparatus under the measurement head. At this time, the surface temperature of the sample changes abruptly and the apparatus records the evolution of heat flow.
This apparatus evaluates various parameters, such as:

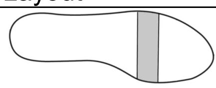
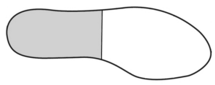
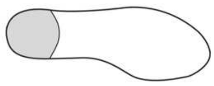
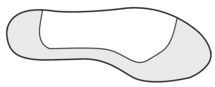
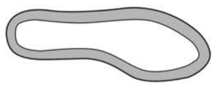
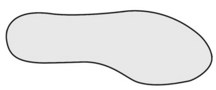
- λ (10^{-3}) – thermal conductivity (W/m°K);
- a (10^{-6}) – thermal difusivity (m^2/s);
- b – thermal absorption ($Ws^{1/2}$/m°K);
- r (10^{-3}) – thermal resistance (m^2°K/W);
- q – heat flow (W/m^2)
- h– thickness of the material (mm).

3. Development of a new protective insole

3.1 Benchmarketing

The anti-penetration inserts still have several flaws that undermine the comfort and reliability of safety shoes. In order to improve this component, this work aims the development of a new and innovative penetration resistant insert that can be more acceptable by the workers.
The starting point of this study was a detailed analysis of the inserts available in the market, whose results allowed us to understand what the most important characteristics of the inserts are. Thus, we were able to conclude that the properties imposed by the safety shoes standards are: penetration resistance; anti-corrosion and fatigue resistance; the main properties are flexibility in the frontal zone of the insert and anti-torsion in the heel zone; and at last, the secondary properties of the penetration resistant inserts are protection against heel injuries, anti-fungi properties, lateral protection, low thickness, permeability, good adhesion to the outsole, low weight, be metal free and impact damping. With these properties in mind, we were able to create a relation between the main properties of the inserts and the area of the foot where they are required as can be seen in Table 1.

Table 1: Penetration resistant insert characteristics and foot area where they are required relation.

Characteristics	Layout
Flexibility	
Anti-torsion	
Heel protection	
Confort	
Adhesion to outsole	
Penetration resistance Antifungal Impact damping Energy distribution	

Therefore, chemical, metrological and destructive tests were performed to the normally used materials, (steel and aramid). These tests allowed us to acquire the necessary information about the inserts tensile strength, thickness and chemical composition and to select new materials to be applied in this component. The analysis of this information was a baseline to the selection of new innovative materials to be applied in this component.

3.2 Penetration tests

Due to some of their properties like flexibility, light weight and their good mechanical properties aramid fiber, polypropylene and ultra-high molecular weight polyethylene based materials were selected and tested according to the standards. The results of these tests were helpfull to see if these materials were suitable options for the new insert.

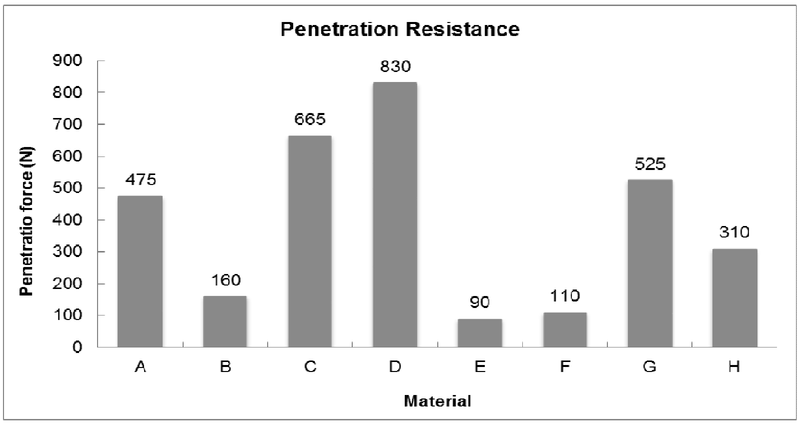


Figure 1: Penetration resistance of the selected materials.

As can be seen in Figure 1 we were able to conclude that use any of this materials alone would not be an option due to their penetration resistance forces, so combinations of these materials according to their prices and availability were made. Materials A, E, F, G and H were combined and tested to penetration (Figure 2).

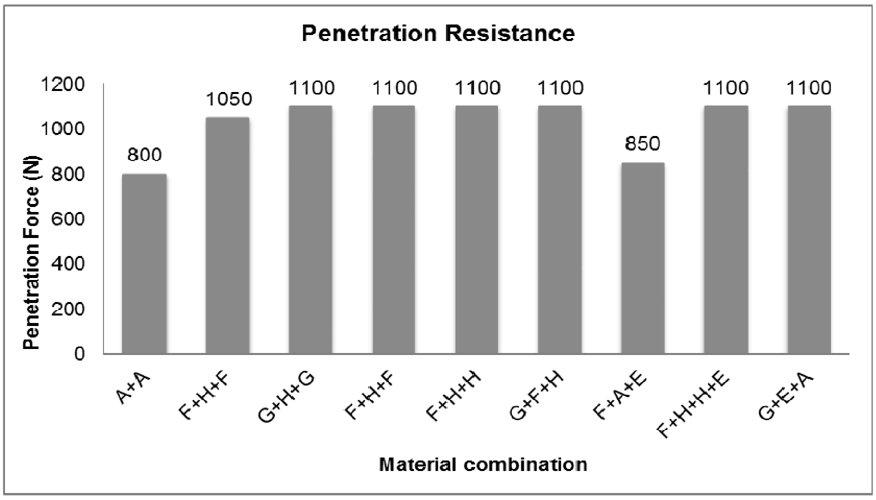


Figure 2: Penetration resistance of the selected materials combinations

3.3 Comfort tests

The comfort properties of the selected materials were tested in order to find a new material that induces better comfort than the standard material. The properties were compared with the aramid properties to see if the replacement of aramid for any of these materials is profitable in terms of comfort. Since air permeability and the thermal properties are the most important variables in comfort sensation, these variables were tested and the results were used to select the right material.

3.3.1 Air permeability

To confirm the purpose of this project in terms of comfort, we compared the present materials used, with the selected materials for the air permeability (Figure 3). Through the values presented in Figure 3 it is possible to assume that only the replacement of the existing aramid insole with material A is not advantageous for the foot breathability.

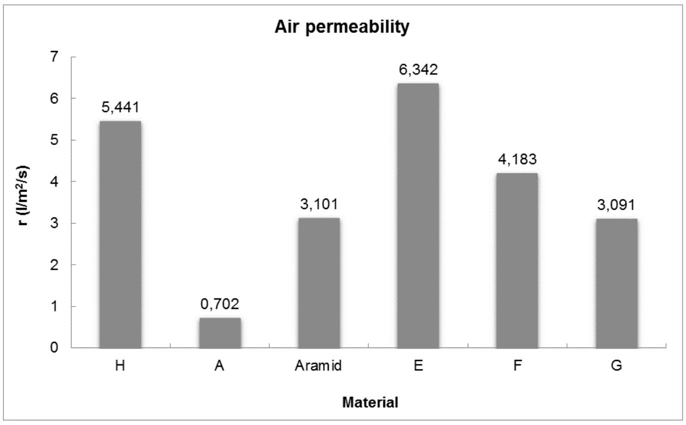
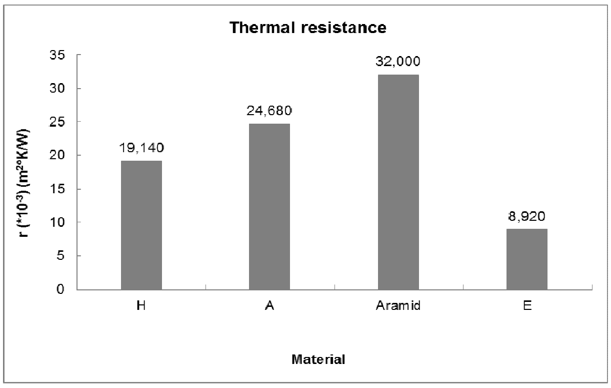


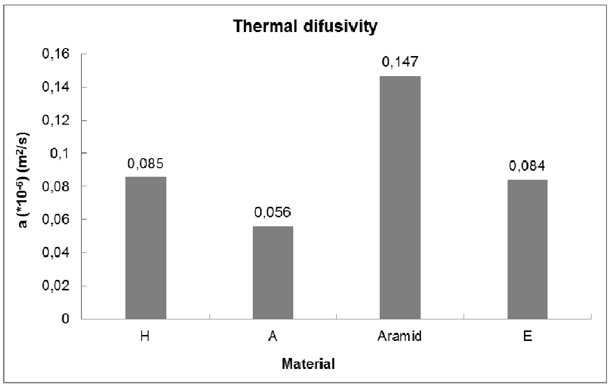
Figure 3: Air permeability of the tested materials.

3.3.2 Thermal properties

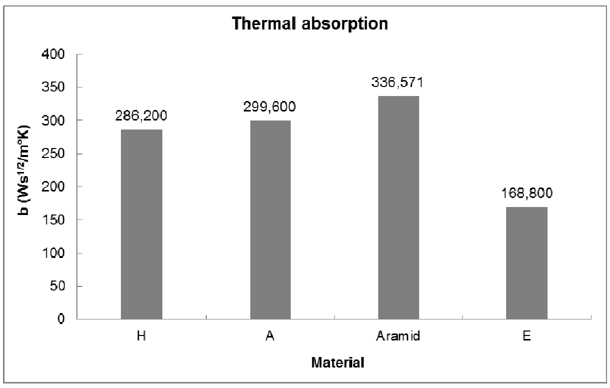
The thermal properties of the materials were tested using the Alambeta device. Through this technique it was possible to determine the thermal resistance, the thermal absorption, the thermal diffusivity. It was also possible to determine the thickness of the materials that is one of the main factors of the aramid insole replacement. As materials F and G are two and four layers of material E, in this test only will be represented material E. As can be seen in Figure 4, the thermal properties of aramid are better than the ones of the new materials. In Figure 5 can be seen the thickness of the aramid and the new materials. The thickness is one of the main factors for the aramid replacement as it is one of our goals to decrease the thickness of the available inserts. It is possible to conclude that the replacement of the aramid for any of the materials or for the materials combinations would advantageous.



(a)



(b)



(c)

Figure 4: Thermal properties of the tested materials: (a) thermal resistance, (b) thermal diffusivity, (c) thermal absorption.

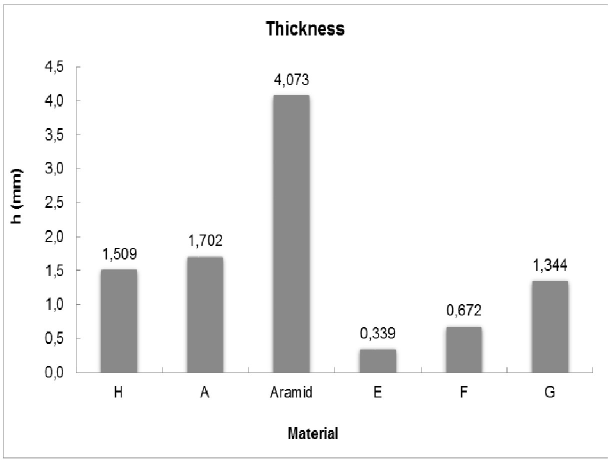


Figure 5: Thickness of the tested materials.

4. Conclusions:

In past few years, the large number of accidents at work continued to result in serious injuries to a large percentage of workers. Focused on the increase of comfort and safety of the existing safety footwear, an analysis of this type of footwear and the penetration resistant inserts was made in this work. This analysis allowed to conclude that there are some failures that could be solved if this component was more comfortable and lightweight, but at the same time resistant.
For a correct optimization, several tests were performed on penetration resistant inserts samples. With innovative materials, it would be possible to develop a new insert with increased comfort and lower thickness, without neglecting the safety and reliability of safety shoes. This is the next step of this project: devolping a new protective insole.

Acknowledgments

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5. References:

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