



Developing High-Performance Recycled Nonwoven Structures for Safety Footwear: A Focus on Perforation Resistance

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Abstract. In this work, the polyester waste, which comes from the cutting of anti-perforation insoles, was reused to produce new anti-perforation structures to be incorporated back into the company, thus creating a closed-loop circular economy. Nonwovens were produced by incorporating polyester waste and commercially recycled polyester in an 80:20 ratio, using the needle-punching technique. To increase the perforation resistance behavior of nonwoven, one of the two high performance fabrics were incorporated: basalt or aramid fiber fabric. These structures were manufactured by layers, interleaving nonwovens with layers of basalt/aramid fiber fabric, using needle-punching. Several parameters were studied to improve the perforation resistance of the structures: number of passes in the needle-punching process; number of basalt/aramid fiber fabric layers; nonwoven thickness; layer orientation angle; needling entry angle; compression molding technique. The resulting structures are eligible for certification (>1100N) and achieved a maximum perforation resistance of 1283 N. This study embodies the principles of a closed-loop circular economy, with AMF company (a safety footwear Portuguese company) repurposing its own waste (polyester) to create a new product (insoles), which is then incorporated into their safety footwear.

Keywords: Circular economy · Footwear waste · Insoles · Nonwoven structures · Perforation resistance · Recycling · Safety Footwear

1 Introduction

Global footwear production exceeds 23 billion pairs annually, of which approximately 300 million correspond to safety footwear. This production scale generates substantial waste throughout both manufacturing and post-consumer phases. Safety footwear is designed to mitigate occupational risks, including punctures, lacerations, impacts, and other mechanical hazards [1]. Current estimates indicate that approximately 54.1% of safety footwear is replaced on an annual basis [2]. These discarded products are often landfilled, contributing to environmental pollution [3]. Recycling industrial waste and end-of-life products to create new materials has become an increasingly relevant practice, however, safety footwear is challenging to recycle due to its complexity and multi-material construction [4].

A safety shoe weight typically ranges from 0.9 to 4.4 kg [2] and consists of several key components, including an outer sole, midsole, insole, toe cap, and upper part [5]. Toe caps and midsoles represent a significant portion of safety shoes' overall weight [6] and are considered the most important elements to guarantee the safety of workers in industrial places [7]. Among these components, midsoles provide a crucial function against perforation acting as a barrier to objects including nails and other sharp metals, therefore their perforation resistance is fundamental to ensure user protection, typically described using EN ISO 20345:2022 [8].

Metallic midsoles composed of stainless steel are used for puncture protection because of their low cost and outstanding resistance. Nevertheless, they present disadvantages, such as high weight, low flexibility, and reduced comfort for the user [9, 10].

Technical woven fabrics, known for their lightness, flexibility, and mechanical properties, are an excellent option for overcoming these challenges [4, 11, 12]. Developing sandwich structures that interlayer these fabrics with nonwoven materials (known for their low cost, lightness, and high recyclability) represents an innovative approach to producing anti-perforation midsoles [13, 14].

Among the technical woven fabrics, aramid due to their high toughness and cut resistance offers excellent performance in impact and puncture resistance and is extensively utilised in ballistic materials and high-strength textiles [15, 16]. Additionally, basalt fabrics, a natural and sustainable alternative, are also gaining attention as promising materials due to their mechanical resistance comparable to other high-performance fabrics and their smaller environmental concerns [17].

Nonwoven structures produced through needle-punching of short fibres [13] present the potential for recycling technical fibres while maintaining some of their mechanical properties. The application of nonwovens has already been investigated for diverse applications, including automotive panels, insulation materials, and geotextiles [18], nevertheless, applications in safety footwear midsoles remain unknown.

However, there are some concerns about ensuring uniform resistance across the textile materials, caused by fibre slip during puncture [19]. Additionally, factors such as the type of fibres or textile structure, number of layers, and layer angle orientation can pose a major influence on the energy absorption of the material and its failure mechanisms [20]. Despite these limitations, extensive research has been addressed on multilayer textile structures for ballistic personal protective equipment [16, 20, 21]. However, research on these structures for safety footwear applications has been limited, with only a few publications addressing the topic [7].

To contribute to this field of research, this study aims to evaluate the effectiveness of sandwich structures made of nonwovens, interspersed with either aramid or basalt fabrics, to improve the perforation resistance of safety footwear midsoles. This research will investigate the influence of several manufacturing parameters on puncture resistance. As such, an evaluation will be performed to verify whether combining recycled polyester nonwoven structures with high-performance fibers can create a lightweight, flexible, and puncture-resistant material, while also promoting a more sustainable and environmentally responsible waste management solution for the safety footwear industry. The main

focus is analyse the impact of layer number and angle orientation of structures made from aramid/basalt fabrics and recycled nonwoven on puncture resistance.

2 Materials and Methods

The polyester waste (post-industrial) used in this work, was provided by AMF Safety Shoes, a Portuguese Company. Polyester waste was ground using an S200 Retsch cutting mill equipped with a 1 * 1 cm square-mesh sieve.

To produce nonwoven structures, the needle-punching method was followed and the Cosmatex© Construzione Macchine Tessili machine, type Linea Campioni HL 500, was used. This machine is connected to the needling machine, forming the Automatex© Needling Nonwovens Production Line. To produce nonwoven structures, commercially recycled polyester (from the textile industry) was used as the matrix to maintain the concept of a circular economy.

For nonwoven production (Fig. 1), the fibers were first opened and then processed through the carding stage, where they were formed into a fibrous web with randomly oriented fibers. The thickness of the web was regulated using a cross lapper. Then, the fibrous web was passed through a needle plate, where it was consolidated through the repeated insertion of barbed needles, with the strokes set at 400/min. This method strengthens the fibrous web by interlocking its fibers, achieving cohesion without the use of binding agents. After the optimization process [22], the final nonwoven structure consisted of 80:20 footwear polyester waste and matrix, respectively.

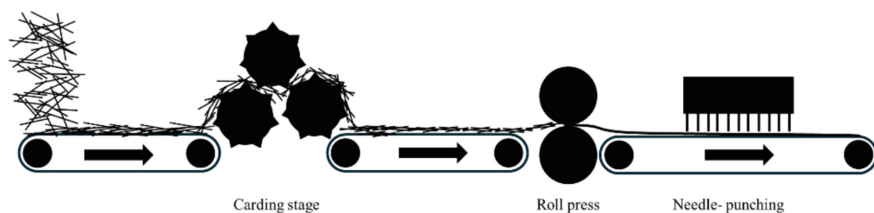


Fig. 1. Depiction of the nonwoven manufacturing process.

2.1 Sandwich Structures Production

To enhance the structures perforation resistance, two materials were selected for their high mechanical strength: basalt fibre fabric and para-aramid fibre fabric [23]. All the produced structures used layers of recycled polyester nonwoven, intercalating with only one of the two layers in each structure: basalt or aramid fiber fabric (Fig. 2).

Several parameters (Figs. 3 and 4) were studied to the structures improve perforation resistance: number of needle passes; compression molding; number of basalt/aramid fibre fabric layers; nonwoven thickness; needling entry angle; layer orientation angle. The basalt/aramid fibre fabric thickness was uniform across all samples. To investigate



Fig. 2. Materials used to produce the structures. a) Recycled polyester nonwoven; b) Basalt fibre fabric; c) Aramid fibre fabric.

the effect of the number of needle passes, the study was conducted using a single nonwoven layer. The material was always needle-punched uniformly on both sides, maintaining the same number of passes. Needle passes of 2, 4, 8, and 12 were evaluated.

The effect of compression molding was investigated to assess whether applying pressure and temperature could enhance the densification, structural integrity, and mechanical performance of the multilayer nonwoven assemblies. To this end, sandwich structures were first fabricated via needle-punching, consisting of two nonwoven layers enclosing a basalt or aramid fabric core. A subset of these samples was then subjected to compression molding without the addition of any thermoplastic matrix, relying solely on controlled temperature and pressure to consolidate the layers. This approach allowed a direct comparison between compressed and uncompressed specimens. The samples were compression molded at 60 kN and 220 °C for 4 min using LabManual300 - Fontijne Presses.

The effect of the number of layers was evaluated by varying the nonwoven and basalt or aramid fiber layers, with the number of nonwoven layers always exceeding that of the fabric layers by one. Layer consolidation was achieved through needle punching.

To assess the influence of nonwoven thickness, two structures were produced for each fabric: one with a single fabric layer and two nonwoven layers of 3 mm thickness, and another identical structure with a nonwoven thickness of 7 mm. This design allowed for a direct comparison of how nonwoven thickness affects the structural and mechanical behavior of the sandwich structures.

Two needle entry angles were evaluated, 0° and 45° - to investigate how the angle of penetration affects the consolidation and mechanical performance of the sandwich structures.

Another important parameter is the orientation and stacking sequence of the layers (Fig. 4). In the joined stacking configuration, the aramid/basalt fabric layers are grouped consecutively to form the inner layer, whereas in the interleaved stacking configuration, the orientations are alternated layer by layer between nonwoven and fabric, ensuring a more uniform distribution of reinforcement directions throughout the sandwich structure. In addition, different orientations of the basalt/aramid fiber fabric layers were tested. This variation in internal architecture allows for the analysis of the influence of stacking sequence on the mechanical and structural response of the sandwich structures, enabling the optimization of properties such as puncture resistance.

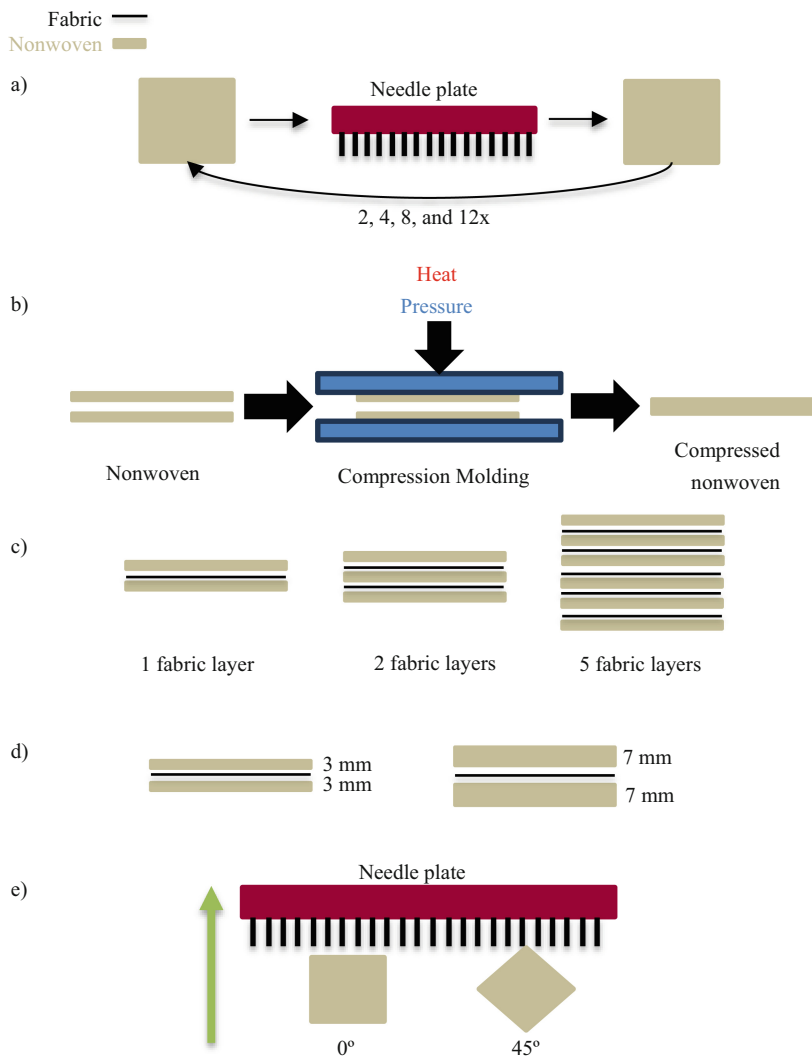


Fig. 3. Scheme of the parameters studied during production. a) number of needle passes; b) compression molding; c) number of layers; d) nonwoven thickness; e) needle plate entry angle.

2.2 Mechanical Properties

Perforation resistance was tested per EN ISO 20345 using a Hounsfield Tinius Olsen H100KPS dynamometer with a 2500 N load cell [8]. The sample was fixed between two square steel plates with 2.5 cm circular opening for needle passage. A 0.45 mm diameter needle was used. The sample was secured with four screws, one at each corner, to prevent slipping. In the test, the needle moved downward, perpendicular to the sample, at a speed of 50 mm/min, until the sample was completely perforated. Each square sample

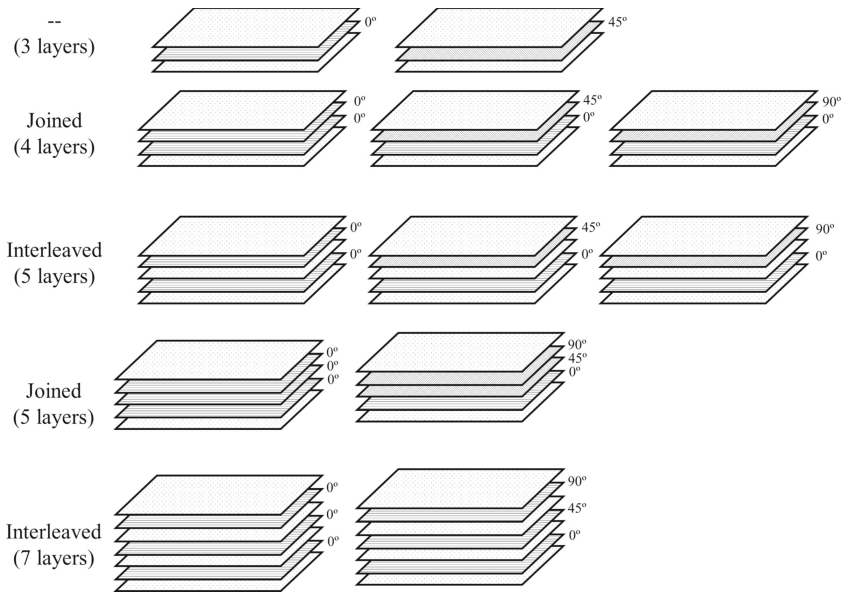


Fig. 4. Layer orientation angle of sandwich structures.

measured $4 * 4$ cm, and ten tests were performed per sample. The value of the perforation resistance must be more than 1100 N [8].

3 Results and Discussion

3.1 Nonwoven Performance

The performance of the nonwoven (without aramid and basalt fabrics) was evaluated prior to the development of the sandwich structures, aiming to determine the optimal number of needle passes required to maintain the structural integrity. Needle passes of 2, 4, 8, and 12 were tested to assess their effect on the structure (Fig. 5). The data shows a decreasing trend in perforation resistance as the number of needle passes increases. The highest resistance, 205 N, was observed with 2 needle passes, while with 12 passes, it dropped to 100 N. The material retains less than half of its original resistance after 12 passes compared to 2, highlighting the progressive weakening and the cumulative effect of repeated perforation. The largest drop in resistance occurs between 4 and 8 needle passes, suggesting a threshold where the material's structural integrity deteriorates more quickly. This suggests that minimizing needle passes is essential for maintaining material integrity over time [24]. Based on these results, the sandwich structures were subjected to only 2 needle passes.

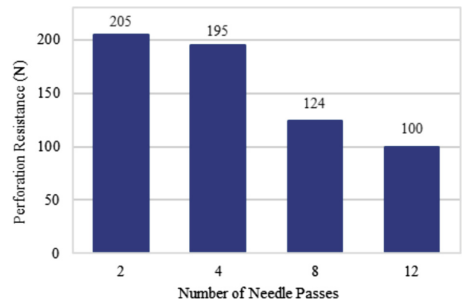


Fig. 5. Influence of number of needles passes on nonwoven perforation resistance.

3.2 Sandwich Structures of Nonwoven with Basalt/Aramid Fiber Fabric

For the development of layered structures incorporating the nonwoven and basalt/aramid fiber fabrics, various parameters were studied individually: compression molding; number of layers; nonwoven thickness; orientation of the fabric and layer distribution; entry orientation in the needle plate. All structures were needled twice, once on each side.

Compression molding

The effect of compression molding on the internal structure and perforation resistance of the samples was evaluated (Fig. 6). In the basalt fiber sample, compression molding improves perforation resistance, with a 28% increase compared to the uncompressed sample. In these samples, compression molding effectively enhances the material’s properties, strengthening its resistance to perforation.

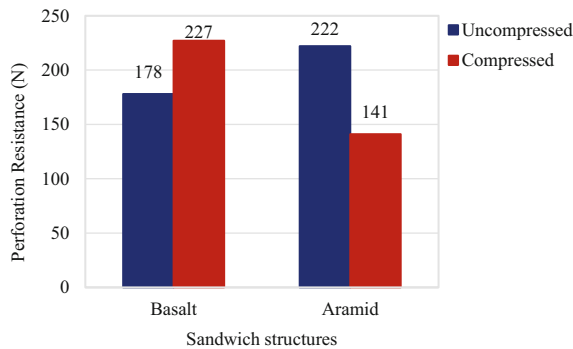


Fig. 6. Influence of compression molding on perforation resistance.

For the aramid fiber samples, the compressed structure exhibited lower perforation resistance (141 N) compared to the uncompressed sample (222 N), reflecting a 36% reduction. This means that loss of resistance potentially occurs due to the realignment and reduction in thickness of the sample, creating fewer gaps or weak points. Additionally, in multi-layered materials, each layer contributes to the resistance by providing separate interfaces that help absorb and redirect force. Compression molding may bond or fuse

the layers too tightly, reducing the “cushioning” effect between layers and limiting the material’s ability to spread out the puncture load.

In the following steps, the samples with basalt fiber were all compressed, while the samples with aramid fiber were not compressed.

Number of layers

Perforation resistance increases significantly with the number of layers (Fig. 7), with a progressive rise from 2% up to 189% and from 8% up to 313% for basalt and aramid fiber, respectively. The highest perforation resistance values, 644 N and 847 N, were both found in the structures with 5 fabric layers and 6 nonwoven layers, with the highest value corresponding to the aramid fiber.

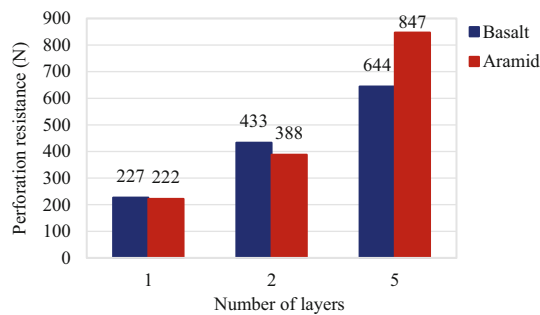


Fig. 7. Influence of number of layers on perforation resistance.

In both basalt and aramid cases, adding layers significantly improves perforation resistance, enhancing overall strength. This pattern supports the idea that more layered configurations could enhance performance in safety applications by better distributing force and increasing the puncture resistance threshold.

Although, due to the maximum thickness allowed for the insoles, a maximum of 3 layers of basalt and aramid fabric were established.

Nonwoven thickness

The influence of nonwoven thickness on the sandwich structures is shown in Fig. 8. In structures with basalt fabric, the increase in thickness led to an increase in strength from 227 N to 463 N. In the case of aramid fiber structures, this increase in strength was even greater, rising from 222 N to 688 N. The increase in nonwoven thickness leads to an increase in perforation resistance due to the added layers of fibers, which create a denser, more compact structure. This additional thickness disperses the applied force across a larger volume of material, reducing the likelihood of perforation [25].

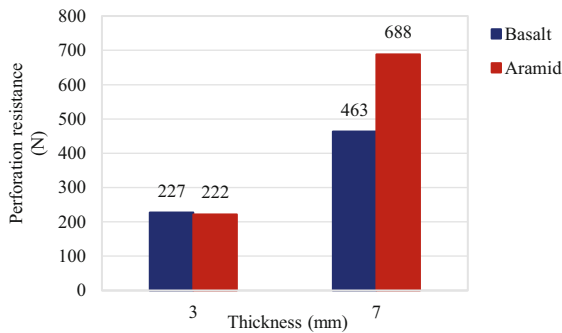


Fig. 8. Influence of nonwoven thickness on perforation resistance.

Entry orientation in the needling plate

Figure 9 describes the results of the influence of entry angle in the needling plate. The entry angle of 45° significantly increased perforation resistance, with an increase of 61% and 69% in the basalt fiber sample and the aramid fiber sample, respectively. While the 0° orientation allows for greater airflow, the 45° orientation significantly enhances the material’s resistance to perforation, possibly by optimizing the distribution of the fibers in relation to the applied force.

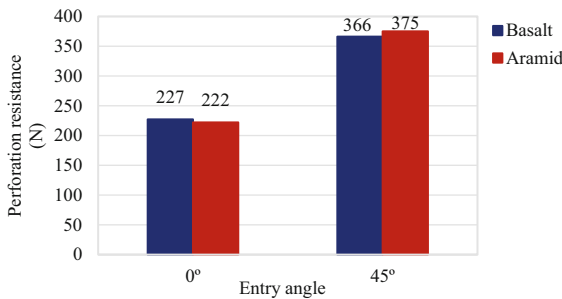


Fig. 9. Influence of entry angle in the needling plate on perforation resistance.

Layer orientation angle

The impact of layer distribution, orientation angles, and interleaved versus joined configurations on perforation resistance was studied for either basalt (Tables 1) or aramid (2) fiber fabrics. For basalt fabric, the inner layer of the sample was formed in the first phase by the continuous distribution of layers of fabric. Two and three layers of basalt fiber fabric were used, and the orientation angles were 0° and 45° for the two layers structure and 0°, 45°, and 90° for the three layers’ structure. In contrast to samples which had an orientation angle of 0°, the perforation resistance values increased by approximately 35% and 11%, respectively.

Table 1. Effect of angles and distribution of basalt fabric layers on perforation resistance

Number of layers		Layers distribution	Angles	Perforation resistance (N)
Nonwoven	Basalt fabric			
2	2	Joined	0°	382
2	3			618
2	2		0°, 45°	515
2	3		0°, 45°, 90°	658
3	2	Interleaved	0°	427
4	3			506
3	2		0°, 45°	433
4	3		0°, 45°, 90°	695

A similar behavior can be observed regarding the interleaving of nonwoven and basalt fiber fabric layers, where orientation at different angles enhanced perforation resistance, demonstrating an improvement of up to 37%, reaching a value of 695 N.

The orientation layers at different angles likely enhances the structure's compaction and interlocking, thereby increasing perforation resistance. Results show inconsistencies in the distribution of interleaved or joined layers. The perforation resistance is higher in the sample with joined layers arranged at angles of 0° and 45° than compared to the similar structure in interleaving layers. On the other hand, when the layers are oriented at angles of 0°, 45°, and 90°, the resistance is higher for the interleaved sample. It is beneficial to interleave at a greater variety of angles (0°, 45°, and 90°) because this decreases points of weakness in the sample and supports perforations that do not follow only one path by creating cross-reinforcement that offers stronger multidirectional resistance [26].

In the presence of aramid fabric, when the structure has 1 layer, the 45° orientation angle provides 58% higher perforation resistance compared to the 0° orientation angle. These results indicate that the 45° orientation angle enhances structural integrity and compaction, improving resistance.

In the presence of 2 joined aramid layers, the highest value, 605 N, was obtained for distribution angles of 0° and 90°. When the layers are aligned at angles of 0° and 45°, perforation resistance decreases significantly to 355 N. When the aramid layers are interleaved, perforation resistance increases when the angles are distributed at 0°-45° and 0°-90°, reaching values of 706 N and 589 N, respectively.

These results show that for angle distributions of 0°-0° and 0°-90°, the layers should be joined, while for 0°-45° angles, the layers should be interleaved. This indicates that the orientation of the fibers influences how forces are transferred and distributed throughout the material, affecting its overall strength and resistance to perforation.

Table 2. Effect of angles and distribution of aramid fabric layers on perforation resistance

Number of layers		Layers distribution	Angles	Perforation resistance (N)
Nonwoven	Aramid fabric			
2	1	—	0°	222
			45°	351
2	2	Joined	0°, 0°	595
			0°, 45°	355
			0°, 90°	605
3	2	Interleaved	0°, 0°	388
			0°, 45°	706
			0°, 90°	589

Combination of the best parameters

A final sample of basalt and aramid fabric was created by incorporating the optimal conditions from the individual parameter analysis (Fig. 10a). The structures consist of 4 layers of nonwoven and 3 layers of basalt/aramid fabric, arranged in interleaved layers at 0°, 45°, and 90° angles. The samples were fed into the needle plate at a 45° angle and needle-punched twice. The main structural difference stems from the compression molding, which was applied exclusively to the basalt fiber sample.

The perforation resistance of the basalt fabric structure was 818 N, the best result among all constructions with this fabric. However, the 1100 N required for safety footwear certification was not met.

For aramid sample, the perforation resistance was 1283 N. This value meets the requirement set by the safety footwear certification standard (> 1100 N), meaning that this sample can be incorporated into safety footwear.

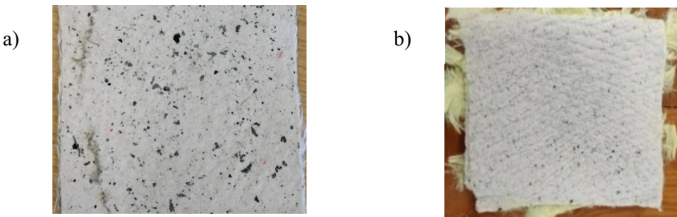


Fig. 10. Final structures. a) Basalt fibre; b) Aramid fibre.

4 Conclusion

In summary, this study highlights the significant impact of several parameters on the perforation resistance of sandwich structures made from nonwoven and basalt/aramid fiber fabrics. The results demonstrate that all parameters have a direct influence on perforation resistance. It is crucial to minimize the number of needle passes to preserve the

integrity of nonwoven materials. Compression molding technique enhances perforation resistance in basalt fiber fabric but has the opposite effect on aramid fiber fabric. Increase the number of layers and their thickness improves perforation resistance. Multi-layered configuration with interleaved layers at angles of 0°, 45° and 90° shows the greatest improvements in resistance. A 45° entry angle on the needle plate significantly boosts perforation resistance.

The sandwich structure with the best parameters for aramid fiber fabric exceeded the required perforation resistance for safety footwear standards. This highlights the importance of selecting processing conditions to enhance material performance.

Future research will focus on additional requirements, such as impact absorption, abrasion resistance, and durability, to facilitate the introduction of this material in safety footwear. Life cycle assessment studies will also be conducted.

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