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Capacete para a micromobilidade elétrica

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Head Protection for Electric Micromobility

Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia e Design de Produto, realizada sob a orientação científica do Investigador Auxiliar em regime laboral Doutor Fábio António Oliveira Fernandes, do Departamento de Engenharia Mecânica da Universidade de Aveiro, e sob a co-orientação do Professor Doutor Eduardo Jorge Henriques Noronha, Professor Auxiliar Convidado do Departamento de Comunicação e Artes da Universidade de Aveiro.

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o júri

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palavras-chave

micromobilidade elétrica, trotinete, sistema de partilha, proteção, traumatismo, capacete

resumo

A micromobilidade elétrica (EMM) apareceu recentemente como uma solução prática para passageiros de curta distância e vem crescendo a taxas muito elevadas graças à introdução de serviços de partilha. Na verdade, a mobilidade urbana mudou drasticamente na última década, e a mobilidade elétrica e a micromobilidade mudaram o panorama nas grandes metrópoles, dada sua acessibilidade, grande disponibilidade, potencial para economizar tempo em viagens curtas e também por ser uma alternativa com grande potencial sustentável em certos cenários. A desvantagem da micromobilidade elétrica tem sido o rápido aumento de lesões e fatalidades. Pesquisas realizadas em diferentes urgências hospitalares demonstram que os traumatismos cranianos estão a tornar-se um dos tipos de lesão mais comuns entre os acidentados com trotinetes elétricas, juntamente de fraturas ósseas, abrasões e lacerações. A evolução das medidas de segurança e das legislações não acompanhou uma mudança tão drástica nas tendências de mobilidade. Isso é evidente ao observar como alguns países estão a ter muitas dificuldades com a categorização dos veículos de micromobilidade e com regulamentos para uso e teste de capacete.

Neste trabalho, as razões por trás das baixas taxas de uso de capacete são explicadas e uma abordagem do ponto de vista do design é feita para tentar solucionar o principal problema a ela associado: a falta de conveniência. Além da inadequação dos capacetes existentes para os sistemas de partilha, também há um problema com sua sustentabilidade, uma vez que não só os componentes são difíceis de separar, mas também alguns deles, como o forro, geralmente são feitos de poliestireno expandido (EPS), espuma a qual não é reciclável. A literatura tem demonstrado que a cortiça, um material celular natural, tem um grande potencial para substituir as espumas sintéticas em aplicações que envolvem proteção contra impactos. Assim, campanhas experimentais envolvendo testes de impacto dinâmico foram realizadas em cortiça e outros novos materiais promissores no campo da absorção de energia, como fluidos reoespessantes, para avaliar as melhores combinações com o intuito de substituir os materiais padrão usados pela indústria de capacetes. Posteriormente, uma validação dos testes de impacto foi feita no Abaqus, o que permitiu uma simulação numérica do teste de atenuação de impacto da norma EN 1078 com um capacete genérico numa “headform” a fim de verificar a espessura ideal do forro.

O resultado final é um capacete inovador que pode ser planificado até o tamanho de um portátil quando não se está em uso e facilmente armazenado numa mochila. Além disso, sua pegada de carbono é 42% menor que a de um capacete padrão, além de poder ser totalmente desmontado e reciclado. Representa uma grande inovação para a indústria de capacetes não só nos aspetos estéticos e funcionais, mas também no que diz respeito à sustentabilidade, tendo o conceito atendido três das dezassete metas estabelecidas pela agenda da ONU 2030 para o desenvolvimento sustentável.

keywords electric mobility, e-scooter, sharing service, road safety, head injury, helmet

abstract

E-micromobility (EMM) has recently appeared as a practical solution for short-distance commuters, and it is growing at upsetting rates thanks to the introduction of sharing services. In fact, urban mobility has drastically changed over the last decade, and electric mobility and micromobility changed the panorama in larger metropolises, given their accessibility, large availability, and the potential to be a time saver in short trips and a potentially sustainable alternative in particular scenarios. The downside of portable e-transportation is the rapid increase in injuries and fatalities. Focusing on standing e-scooters, head injuries are becoming one of the most common as shown by research conducted in different urban emergency departments, alongside bone fractures, skin abrasions, and lacerations. The evolution of safety measures and regulations did not keep pace with such a drastic change in mobility trends. This is evident considering how some countries are struggling with vehicle categories and regulations for helmet use and testing.

In this work, the reasons behind the low rates of helmet use are explained and a design-based approach is taken towards the main problem associated with it: the lack of convenience. Besides the inadequacy of existing helmets for the sharing systems, there is also a problem with their sustainability since not only the components are difficult to separate but also some of them, such as the liner, are usually made of expanded polystyrene (EPS), a foam that is not recyclable. Literature has proven that cork, a natural cellular material, has a great potential to replace synthetic foams for applications that involve impact protection. Therefore, experimental campaigns involving dynamic impact tests have been conducted on cork and other new promising materials with energy absorption capabilities, such as shear thickening fluids, to evaluate the best combinations for replacing the standard materials used by the helmet industry. Afterwards, a validation of the drop tests has been done in Abaqus, which allowed for a numerical simulation of the EN 1078 standard's impact attenuation test with a generic helmet on a headform in order to verify the optimal thickness of the liner.

The final result is an innovative helmet that can be flattened to about the size of a laptop when not in use and be easily stored in a backpack. Furthermore, its carbon footprint is 42% lower than of a standard helmet, besides being able to be fully disassembled and recycled. It represents a big innovation for the helmet industry not only in aesthetical and functional aspects, but also regarding sustainability, having the concept met three of the seventeen goals established by the UN 2030 agenda for sustainable development.

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1. Introduction

Since its introduction in 2017, the shared e-scooters have grown exponentially, on a global scale, mainly because of their affordability, low environmental footprint, and convenience (Choron & Sakran, 2019). In the United States (U.S.), where shared e-scooters services became first available, 38.5 million trips were registered in 2018, surpassing by 2 million the number of trips registered for the station-based bike-sharing in the same year (NACTO, 2018). That represents tremendous growth in just over a year of existence. More impressively, in the following year, e-scooters alone were already responsible for over 63% of all shared micromobility trips in the U.S., which represents an increase of over 100% on trips taken on e-scooters nationwide – 86 million – when compared to 2018 (NACTO, 2019). This unprecedented growth that also rapidly spread from the U.S. to the rest of the world, has perhaps made the e-scooters become, in record time, the most popular type of shared e-micromobility in cities worldwide.

Smith and Schwieterman (2018) have shown in their case study that e-scooters are more efficient in short-distance trips comparing to public transits and walking since dockless e-scooters can fill the void caused by limited transit coverage available for intra-neighborhood trips. Although Smith and Schwieterman's case study is based on a multimodal travel model that evaluated approximately 30 thousand randomly selected hypothetical trips between several locations in the city of Chicago, it showed that e-scooters users can quickly access the vehicles, and they can be parked directly at their destination, all of which can help reducing travel time up to 3 minutes for distances of up to 3.21 km. According to a measurement made by the National Household Travel Survey, 35% of all the car trips in the United States are under 3.2 km, which means that having structured micromobility options can potentially help people make these trips without relying on private cars that ultimately cause congestion and contribute to air pollution (NACTO, 2019). Furthermore, Oeschger et al. (2020) demonstrated how integrated transport systems, e.g. a solution integrating e-scooter and public transport, have the potential to be a competitive alternative to private cars.

In Vienna, Austria, Laa & Leth (2020) found out that people are more likely to use e-scooters to replace walking trips, followed by bus and tramways. Most importantly, e-scooters are commonly used in combination with one or two other modes of transportation as shown by the studies of Lefrancq (2019) and 6t-bureau de recherche (2019) conducted in Belgium and France, respectively. In Singapore, the Land Transport Authority launched a program called 'Travel Smart Journeys', which is about stimulating the public to use alternative transportation, such as e-scooters, to replace short-distance metro trips during peak hours, and therefore, help to alleviate congestion (Cao et al., 2021). This demonstrates the great potential of this micro-vehicle for short-distance trips, particularly first/last mile ones.

However, despite its benefits as an alternative means of transportation for cities that have been increasingly suffering from excessive amounts of cars in the streets and the saturation of public transportations, some problems come along with it. Because of the immensely fast speed in which this sharing system developed and established itself, the governments, in general, did not act as fast by terms of regulating the activity, ultimately leading to a growing number of personal injuries resulting from e-scooter use and the consequent increase in the number of entries for such related injuries at the hospitals' emergency departments (Austin Public Health, 2019; Badeau et al., 2019; Blomberg et al., 2019; Bloom et al., 2020; Sikka et al., 2019; T. K. Trivedi et al., 2019).

The resulting rise of injuries is particularly worrying given that many were to the head. Traumatic brain injuries (TBI) and other head injuries account for a large portion of injuries suffered in accidents involving e-scooters - 33.3% of the cases in Auckland, New Zealand (Mayhew & Bergin, 2019), and 40.2% in Santa Mónica, California (Trivedi et al., 2019). Directly linked to the high numbers of severe head injuries is another disquieting observation: the rate of helmet use in shared micromobility is shockingly low, especially in cities where its use is not mandatory by law. For instance, the highest use rate amid the reviewed studies comes from Brussels, Belgium, with only 7% (Lefrancq, 2019), and the lowest reaching 0% (Badeau et al., 2019). The average rate across all the studies, which also includes cities where the use of a helmet is mandatory and, consequently, higher, is 9.28%. It is evident that head protection is a major issue in shared micromobility, and properly addressing it can greatly reduce hospitalizations and serious outcomes such as disabilities and fatalities.

The shared e-scooter services are a recent phenomenon, and their impacts on public health are not yet fully known. In order to understand the factors behind the ever-growing number of injured in e-scooters accidents and determine possible solutions, the following sections within the state-of-the-art will give a detailed overview on topics related to safety in micromobility. First, by exploring and understanding what shared micromobility is and who its users are. Then, by analyzing the legislation in place and how it affects the use of the vehicles and the safety of the riders. Next, by reviewing studies concerning accidents with e-scooters in order to depict the most common injuries – fractures, lacerations, abrasions, and head injuries – and their impacts on public health. Then, head protection's low usage rates, the potential causes, and consequences will be discussed and analyzed. Furthermore, a review on current helmet standards will be carried on, discussing the differences amongst the existing ones, and focusing on the testing methods and criteria. Current head protection solutions available on the market will be explored and, at last, a critical assessment will be given with recommendations towards future trends, sustainability, circular economy, design requirements, and legislation. After the theoretical foundation of the work contained in the state-of-the-art, that is essential to understand what the problems are and what lies behind them, the sections that follow will be dedicated to the experimental campaign and the product development.

This work's main objective is to fill the identified existing gap in terms of head protection equipment for the shared micromobility in order to bring more convenience to the users and consequently help to increase the helmet usage amongst them.

2. State of the art

2.1. Defining micromobility

The category of micro-vehicles is quite broad, ranging from human-propelled vehicles to electric and internal-combustion ones, with speeds typically reaching up to 45 km/h. There is no universal definition for the category, and it varies across the world. ITF (2020) considers micro-vehicles to have no more than 350 kg, a top speed of 45 km/h, and kinetic energy limited to 27 kJ – which is about one hundred times less the kinetic energy of a compact car at its top speed. As it is possible to see in ***Fig. 1***, this category is heterogeneous, and the vehicles cannot be defined by their form nor by their propulsion method since they do not share a common ground in either of these. Therefore, disparate vehicles such as kick-scooters and mopeds can fall into the same category of micro-vehicles if they do not exceed the defined mass and top speed mentioned above.

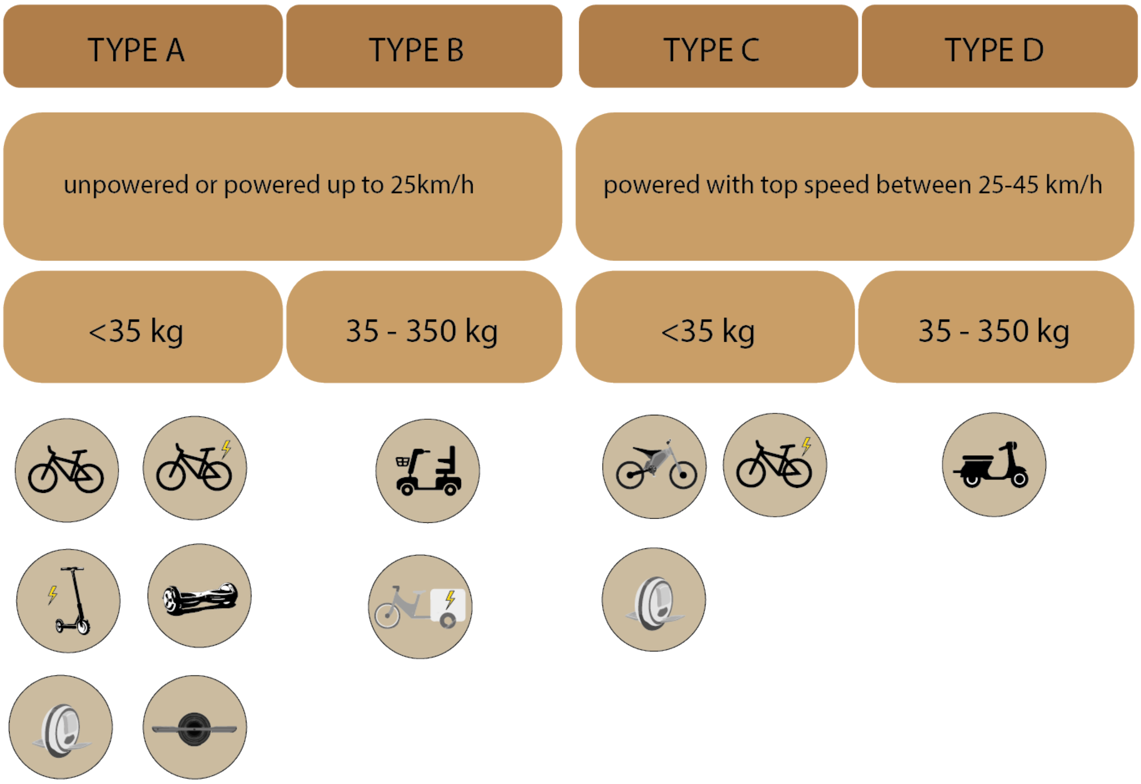


Fig. 1 - Micromobility classification proposed by ITF (2020). Adapted from ITF (2020).

Besides the International Transport Forum (ITF) efforts to address the need of creating a common definition for micromobility, the SAE international – the U.S.A. based Society of Automotive Engineers (SAE) – has also aimed to classify micro-vehicles. Their Standard J3194™ distinguishes micromobility from powered micromobility, with the latter being a category of powered vehicles (electric motor or a combustion engine) and containing six types of micro-vehicles: powered standing scooter, powered seated scooter, powered bicycle, powered self-balancing board, powered non-self-balancing board and powered skates (SAE International, 2019).

	Powered bicycle	Powered Standing Scooter	Powered Seated Scooter	Powered Self-balancing board	Powered Non-Self-balancing board
	Y	Y	Y	Possible	N
Seat	Y	N	Y	N	N
Operable pedals	Y	N	N	N	N
Floorboard / foot pegs	Possible	Y	Y	Y	Y
Self-balancing	Y	N	N	Y	N

Fig. 2 - Classification of Powered Micromobility according to SAE. Adapted from SAE international (2019)

Despite the effort of international organizations such as the ones mentioned above, governments around the world either include these vehicles within existing categories or eventually create their own. For instance, South Korea considers power-driven vehicles to be a part of motor vehicles. On the other hand, Singapore created a category called “personal mobility device” (ITF, 2020).

2.1.1. Shared micromobility

Economic models based on sharing includes a wide range of sectors that goes from lodging to job agencies all the way to the transportation sector, the latter being a more recent phenomenon that disrupted what had been an intrinsic part of most of the western societies’ culture: the emphasis on personal vehicle ownership (Shaheen & Chan, 2016). Shared mobility consists in the shared use of a motor vehicle – bicycle, scooter, car, and others – and it is a service often, if not exclusively, enabled by technology, through smartphone applications. Customers can download the preferred company’s mobile application into their phones, and it will direct them to the nearest available e-scooter/bicycle via global positioning system (GPS). Once the ride has been completed, customers can leave the vehicles in the areas indicated by the mobile application (Allem

& Majmundar, 2019). These services can greatly contribute to changes in people's travel behaviors as it increases the number of available options for a trip, reduce travel uncertainty, and provide easier access to a vehicle, particularly for the individuals that do not own one (Circella et al., 2018).

Sharing services enable people to benefit from using vehicles without the downside of private ownership – namely maintenance costs, fuel, insurance – especially in carsharing. Such benefits have contributed to the growth of the industry, which, by October 2018, registered 4.8 million carsharing members worldwide - of which 2.2 million in Europe and 1.6 million in North America (Shaheen & Chan, 2016). In parallel, bike and e-scooters sharing services have seen greater growth: 207 million trips on shared bikes and e-scooters since 2010 in the U.S., and 84 million of them took place solely in 2018 (NACTO, 2018). While carsharing focuses on replacing long-distance trips, bike-sharing addresses those short last-minute trips and has the potential to replace public transport. As shown by Buck et al (2013), in a study conducted with users of the bike-sharing program in Washington D.C, 35% of casual users claimed they use the service to replace public transport trips. For those living in the city's outskirts, where sometimes access to public transportation by walk is limited, bike-sharing services can also increase transit use by facilitating access to them (Martin & Shaheen, 2014).

The e-scooter sharing service, the youngest of them, came out in the United States in 2017, and only after one year of existence, in 2018, it had already surpassed bike-sharing in the annual number of trips – 38.5 million against 36.5 from bikes – with a fleet of around 85.000 scooters spread over 100 U.S. cities (NACTO, 2018). The e-scooters have the advantage of being dockless, allowing the customer to leave it virtually anywhere. This is a facilitator for many people since one does not need to waste time searching after a docking station and can more likely park closer to its destination. Similar to the shared bicycles, shared e-scooters fulfill the purpose of acting as a connection to public transportation and, in some cases, replace them.

In Vienna, Austria, Laa & Leth (2020) found that around 35% of rental e-scooters customers often use these vehicles to replace walking trips and 25% to replace bus and tram trips. In Belgium, this number proved to be even higher, with 51% of the customers reporting that they replace one or more transit trips with the e-scooters and 40% use them in combination with other types of transportation (Lefrancq, 2019). Additionally, the e-scooter sharing service is also appealing for tourists as suggested by 6t-bureau de recherche (2019), which aimed to trace the profile of free-floating e-scooter services by interviewing the customers, concluding that, in France, 42% of them were tourists making use of the service due to its practicality.

E-scooter rental companies claim that their shared e-scooter services are environmentally friendly and sustainable since they reduce the use of cars and their negative impacts on the planet (Bird, 2019a). These arguments attract customers that are environmentally conscious as suggested by Lefrancq (2019), based on the significant percentage of users (27%) saying they use shared e-scooters in order to help reduce air pollution and other 13% to reduce their ecological footprint. Besides, environmental factors also play a major role in people’s willingness to start using e-scooters for work/school trips (Glavić et al., 2021). And although it is evident the efficiency of electric vehicles, and how vehicle size affects it (Weiss et al., 2020), depending on the scenarios, such conclusions cannot be withdrawn straightforward, as highlighted by recent studies (de Bortoli & Christoforou, 2020; Hollingsworth et al., 2019; Severengiz et al., 2020). Hollingsworth et al (2019) showed how important it is to keep in mind that, although e-scooters are an effective solution to traffic jams and a good replacement for short trips, it does not necessarily mean a significant reduction of the environmental impacts from the transportation system as highlighted by the life cycle assessments considering the e-scooters materials, manufacturing processes, etc.

Scenarios can prove to be disparate depending on several factors: collecting of e-scooters to recharge the batteries, the energy sources, among others. According to

Severengiz et al (2020), in the best-case scenario, if the sharing services use electrified vehicles to collect the scooters, renewable sources of energy for recharging batteries, and have scooter models with swappable batteries, its global warming impact would be of 64 gCO_2eq per passenger per kilometer. This is much lower than a passenger of car (147 gCO_2eq) and bus (80 gCO_2eq), but still higher than e-bikes (40 gCO_2eq). In practice, to fully achieve the benefits associated with electric motors, namely more energy efficiency and less pollution, it is necessary to take a holistic view of integrating micromobility with other types of public transit, in a structured way, for decreasing the lifecycle environmental effects associated with their use (Abduljabbar et al., 2021). Nevertheless, the replacement of car trips by e-scooters would vastly improve community health by removing noise, air pollution, and road danger sources from the streets (ITF, 2020).

For several reasons, the micromobility market has an enormous potential to expand even further. The use of micro-vehicles can benefit individual travelers and communities by addressing gaps in transportation networks, reduce the usage of cars, and improve mobility access for low-income communities (Shaheen & Chan, 2016). The advantages go beyond the mobility itself, with businesses profiting from an increase in economic activity near multi-modal hubs and commercial areas (Buehler & Hamre, 2015). It is estimated that micromobility can capture between 8% to 15% of trips under 8 km and has a market potential of $200B to $300B in the United States, $100B to $150B in Europe, and $30 to $50B in China (Heineke et al., 2019).

2.2. Legislation – the case of e-scooters

The fact that there is a discrepancy in the classification of micro-vehicles amongst different countries and governments, leads to a few problems concerning the proper regulation of some of these vehicles – such as e-scooters. In the United States, for instance, e-scooters are regulated at each different state of the federation. However, by the end of 2018, only ten states had defined scooters in statutes, even with the exponential growth in popularity of this transportation method (Sikka et al., 2019). According to a report from Benedicto et al. (2021), the state of California has fully regulated the use of e-scooters, while the state of Hawaii consider them to be completely illegal, and the state of Alaska has not yet addressed the issue, treating such vehicles as belonging to the broader category of “motor-driven cycles” instead. This shows that policymakers are struggling to deal with this new type of transportation and, as a consequence of this diversity in local legislations, riders find it more difficult to know what is allowed and law enforcement officials might face a greater challenge addressing unsafe behaviors (GHSA, 2020).

Similarly, in the European Union (EU), each member state has its regulation concerning e-scooters. Nevertheless, the EU regulation Nº168/2013 (European Parliament, 2013) establishes the L-category for powered vehicles, acting as a reference to facilitate the adoption of legislation concerning these types of vehicles. The L-category is subdivided into seven, going from L1a to L7a, and some types of micro-vehicles can be fitted into the L1e category called “light two-wheel powered vehicle”, which consists of electric bicycles and any two-wheel vehicle with a maximum speed of 45 km/h and a net power of up to 4000 W (ITF, 2020). Nonetheless, despite the reference to “two-wheel powered vehicles”, Article 2(2)(i) excludes “self-balancing vehicles” and the 2(2)(j) eliminates “vehicles not equipped with at least one seating position” from the range of vehicles to which the Regulation applies, making it irrelevant for e-scooters (Sokołowski, 2020). In the absence of an EU legislation that encompasses electric scooters, Sokołowski (2020) went through the national legislations of the 27 EU member states and the UK to find out whether or not these vehicles are recognized by law, and concluded that twenty-one of them address electric scooters.

Then, as in the United States, there is a significant difference in how these vehicles are regulated amongst the member states. A study by Kamphius & van Schagen (2020) consisting of a survey with 18 member countries of the Forum of European Road Safety Research Institutes (FERSI) about e-scooters legal status, usage, and safety, indicates that there is a tendency in many of these countries to legally define such vehicles as bicycles. However, there are nuances to this categorization: in Sweden, an e-scooter with a 250 W motor is considered to be a bicycle but can be classified as a moped class I or II if it exceeds that limit. In Finland, if the scooter has a top speed of 15 km/h, it is defined as a pedestrian. Another confusing case is the UK one, where e-scooters are classified as Personal Light Electric Vehicles (PLEVs) and are currently not allowed on the roads, failing to address the mandatory law requirements. Therefore, e-scooters cannot fulfill the requirements for motor vehicles, such as signaling ability, neither having license plates (Hourston et al., 2021).

Table 1 - Main findings of Kamphius & van Schagen's study summed up graphically. The green check means 'applicable', the red cross means 'not applicable' and the blank space means 'no clear information'.

	AT	BE	CZ	DK	DE	EL	FI	FR	HU	IT	NL	NO	PL	PT	RS	ES	SE	CH
Helmet obligation	✓	✗	✓	✗	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗
Specific category for e-scooters	✓	✓	✗	✗	✓	✗	✗	✓		✗	✗	✗	✗	✗	✗	✓	✗	✗
E-scooter allowed on cycling path	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✗	✗	✓	✓	✗		✓	✓
E-scooter allowed on sidewalk	✗	✓	✗	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗
Speed limit	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓		✓	✓	✓	✓
Age restriction to use e-scooters	✓	✗		✓	✓	✗	✗	✓	✗	✓	✗	✗	✗	✓	✗	✗	✗	✓
Mandatory insurance	✗	✗	✗	✗	✓	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
E-scooter in public spaces	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓

AT = Austria; BE= Belgium; CZ= Czech; DK= Denmark; DE= Germany; EL= Greece; FI= Finland; FR= France; HU= Hungary; IT= Italy; NL= Netherlands; NO= Norway; PL= Poland; PT= Portugal; RS= Serbia; ES= Spain; SE= Sweden; CH= Switzerland

In Asia, Singapore has a more targeted legislation towards e-scooters than any other country in the region. As mentioned in section 2.1, they have created a special category for e-scooters, called “PMD”. Such a category differentiates micro-vehicles from cars, bikes, and e-bikes. The use of vehicles that belong to the PMDs is governed by the Active Mobility Act (AMA), which demands, amongst many requirements, that e-scooters must have a license plate, top speed of 25 km/h, and, as of 30 June 2021, one must take a mandatory theoretical test to be allowed to ride their devices on public roads (SLA, 2021). Besides Singapore, Japan also demands that all e-scooters must have a license plate (ITF, 2020). Although South Korea has a strict legislation with all power-driven vehicles (electric or not) falling into the category of motor vehicles, there is no distinction between the different types (ITF, 2020). However, the government has been acting upon updating the legislation in an attempt to address the existing gaps and has recently revised the country’s Road Traffic Act to make the use of safety helmets mandatory for all e-scooter users (Neuron, 2021).

Overall, it can be concluded that many countries are still struggling with the legal status of this transportation method, and more targeted and detailed legislation is needed. A well-grounded regulation for electric scooters should be easy to understand and remember, allow them to be a convenient transportation option while protecting public safety. In addition, it should be based on use and user, opposite to the current general situation worldwide: rules are often poorly defined, contradictory or inexistent (Fang et al., 2019).

2.3. Who uses shared e-scooters?

Through a variety of studies, represented in ***Table 2***, it is possible to notice a certain pattern in type of users of shared micromobility. Across all the ten studies, except the one in Copenhagen, most of the users are male - averaging 60.11%. Additionally, e-scooters are mainly used by young adults, with the mean age being over 30 in many cases, such as in Los Angeles (35.8), Santa Monica (33.7), and France (36).

Regarding the user's educational level, they are consistently high throughout all of the interview-based studies. In Vienna, Austria, 64.2% of them have at least a bachelor's degree (Laa & Leth, 2020). A study conducted in Thessaloniki, Greece, reported that 35.1% of the interviewed had a bachelor's (Raptopoulou et al., 2021). In Belgium, 53% graduated from university (Lefrancq, 2019), and in New Zealand, around 32% of the interviewed claim to have a postgraduate qualification and more 27% to have a bachelor's (Fitt & Curl, 2019). In addition to the ones who already have a degree, students are also a big part of the users, ranging from 15% (Lefrancq, 2019) to 36% (Raptopoulou et al., 2021).

Table 2 - User's profile across studies

Ref.	Location	Type of study	Male riders (%)	Mean age or age group
1	France	On-street interview	66	36 years old
2	Brussels, Belgium	On-street interview	66	25-34 yers old (44 %)
3	Thessaloniki, Greece	On-street interview	68.6	18-27 years old (73.4 %)
4	Vienna, Austria	Online + On-street interview	75	26-35 years old (43.4 %)
5	New Zealand	Online interview	58	18-34 years old (58 %)
6	Auckland, New Zealand	ED's radiology	57.1	20-29 years old (39.7 %)
7	Los Angeles, California (U.S)	Trauma patients	57	35.8 years old
8	Santa Monica California (U.S)	ED patients	58.9	33.7 years old
9	Copenhagen, Denmark	EMS records	43	18-40 years old (59.8 %)
10	Austin, Texas (U.S)	ED patients	56	29 years old

ED = emergency department ; EMS = emergency medical services

Sources: [1] 6t-bureau de recherche (2019) [2] Lefrancq (2019) [3] Raptopoulou et al (2021) [4] Laa & Leth (2020) [5] Fitt & Curl (2019) [6] Mayhew & Bergin (2019) [7] Bloom et al (2020) [8] Trivedi et al (2019) [9] Blomberg et al (2019) [10] Austin Public Health (2019)

Another conclusion taken by comparing these studies is that e-scooters have indeed a potential to replace short walking trips since most of the interviewed use them to avoid walking – 48% in Brussels (Lefrancq, 2019), around 52% in New Zealand (Fitt & Curl, 2019), 43.9% in Thessaloniki (Raptopoulou et al., 2021), 44% in France (6t-bureau de recherche, 2019) and 35% in Vienna (Laa & Leth, 2020). On the other hand, replacing public transportation seems less likely: 6% in France (6t-bureau de recherche,

2019) and 18% in Vienna (Laa & Leth, 2020). Although these can be combined as shown by the Belgian and French studies – 40% use e-scooters in combination with one or more modes of transport in Brussels (Lefrancq, 2019) and 23% in France (6t-bureau de recherche, 2019).

Overall, most of the users are male, within 18 to 40 years old, upper-to-middle income, with high levels of educational attainment. Their motivation to use e-scooters is mainly to replace short walking trips.

2.4. Accidents on the rise

Alongside the benefits brought by the shared micromobility services, there has also been a rise in concern for the possible safety issues involving e-scooters in the urban environment and their potential risk to public safety. Several recent studies correlate the increase in the number of accidents concerning e-scooters with the recent exponential growth of e-scooters sharing services (Kobayashi et al., 2019; Badeau et al., 2019; Blomberg et al., 2019; Bloom et al., 2020; Namiri et al., 2020). In the publication from GHSA (2020), the authors gathered data from the National Electronic Injury Surveillance System (NEISS) of the United States regarding e-scooters accidents and hospital admissions. The numbers show that there had been an increase of 365% in hospital admissions for e-scooter injuries between 2014 and 2018. More recently, between 2017 and 2018, there was a rise from 8,016 to 14,651 in the number of reported e-scooter related injuries.

Despite the alarming escalation of accidents, e-scooters still present a relatively low risk of fatality compared to other transportation modalities. It is estimated that the risk ranges between 78 and 100 fatalities per billion trips, while for bicycles range from 21 to 257 and between 132 to 1.164 fatalities per billion trips for powered two-wheels (motorcycles and mopeds) (ITF, 2020). Nevertheless, the e-scooter industry is a recent phenomenon and still has a projected growth for the years ahead. Nisson et al. (2020) predict that e-scooters can become more fatal, only behind automobile collisions in related mortality if this growing public health issue is not addressed.

Currently, e-scooters are proving to be more unsafe than bicycles concerning injuries. A study from Namiri et al. (2020), in which they investigated e-scooter related injuries and hospital admissions that had been registered across the United States, concluded that nearly one-third of the patients had a head injury, which means more than double the rate of the same type of injury experienced by bicyclists. Furthermore, Trivedi et al. (2019) analyzed data from two hospitals' emergency departments in southern California and concluded that patients with injuries related to electric scooters are more prevalent than those related to bicycles – 249 emergency department visits from e-scooters accidents against 195 from bicycles – over the same period. The percentage of scooter accidents resulting in serious injuries is high and consistent across many studies: Störmann et al. (2020) found in their investigation in Germany that TBI and fractures represented 56.6% of the cases involving e-scooter related injuries; Mayhew & Bergin (2019) verified that concussions, skull fracture, facial fracture, and intracranial bleed accounted for 38.1% of cases in Auckland, New Zealand. Additionally, in Los Angeles, Bloom et al (2020) found several types of injuries to the head amid 248 patients, more specifically 17 % lacerations, 13 % contusions, 11% abrasions, 8 % closed head injuries, 6 % fractures, 4 % of dental injuries and 2 % contusions. In South Korea, the registered number of patients who suffered traumatic injuries to the craniofacial region was also high, around 48.8% (Kim et al., 2021). In Singapore, the number of e-scooter related injuries and their severity have risen, having also been registered one death caused by severe head injury and hemorrhage, even after the government has regulated the use of e-scooters through the previously mentioned Active Mobility Act (AMA) (Lee et al., 2020).

Many of these outcomes could have been avoided if the riders were using helmets, but all the reviewed studies show a staggering low use of helmets in e-scooter related accidents. The numbers get as low as 1% (Austin Public Health, 2019). This is particularly troubling given the proven efficiency of helmets in protecting against head injuries (Høye, 2018; Olivier & Creighton, 2017) and the known short- and long-term sequelae of head traumas (Blomberg et al., 2019; Störmann et al., 2020).

Besides the head, the studies also show that the body's upper and lower extremities are also commonly affected. The low fall height combined with a short reaction time make the extremities more vulnerable in the event of a fall and, consequently, there is a risk for relevant long-term functional limitations, like permanent instability and reduced range of motion of the injured areas (Störmann et al., 2020). In Santa Monica, amongst 228 riders that went to the hospitals' emergency departments, 31.1% of them had a fracture either in the lower or the upper extremity (Trivedi et al., 2019). In Auckland, New Zealand, the number of fractured victims in the extremities is 41.3% (Mayhew & Bergin, 2019), in Los Angeles 36% (Bloom et al., 2020), and similarly, in Frankfurt, Germany, 38.1% had a fracture of some kind in the same body regions (Störmann et al., 2020). Contusions, abrasions, and lacerations are also amongst the most common types of injuries in the extremities.

The fact that e-scooters are allowed in some places, or at least not specifically forbidden, such as on sidewalks, raises another safety concern: the risk for accidents involving pedestrians. In the study by Trivedi et al. (2019), 8.4% of the patients that had been presented to the emergency department were non-rider pedestrians. Similarly, Blomberg et al. (2019) found out that among the analyzed patients in Copenhagen, 14% were non-riders hit by e-scooters. Sikka et al. (2019) explored how e-scooters affect pedestrian safety based on the case study of a female that was struck by an electric scooter while on the sidewalk. Despite the limitations of the study, pedestrians were found to be more susceptible to severe injuries when hit by e-scooters. Again, this highlights the importance of having effective and clear legislation in place for this micro-vehicle.

The sometimes inconsistent and confusing regulation makes customers ride inappropriately on forbidden places, likely unaware of it. This is the case of Washington D.C, where e-scooters are allowed on sidewalks outside of the central district, but not in it (Sikka et al., 2019). Another issue directly related to the high number of e-scooters accidents that becomes difficult to be tackled due to this diversity and lack of consistency among local legislations is the maximum allowed speed. For instance, the Australian Road Rules allow low-powered motorized scooters to reach the speed of 10 km/h. However, in Queensland, the maximum speed is 25 km/h, whereas in South Australia is 15 km/h. Moreover, in contrast to the legislation adopted by most countries and cities worldwide, the rules in the mentioned states require that most rides occur on sidewalks (N. Haworth et al., 2021). In the U.S., most states limit the speed of e-scooters to 25 km/h, which is about twice as fast as the average speed of individuals riding bicycles through a bike-sharing program. The higher acceleration of an e-scooter increases the potential of e-scooter riders reaching the top speed faster than bicycle, which may reduce the operator's ability to avoid an obstacle or a threat (Todd et al., 2019).

An investigation conducted by Austin Public Health (2019) analyzed accidents related to e-scooters and found that, in 37% of them, excessive speed was the leading cause of the crashes. Polis (2019) points out that the system in which the e-scooters are based (pay-per-minute) is an incentive to excessive speeds, which may not be adequate for specific environments, resulting in dangerous driving. Besides that, according to the Portland Bureau of Transportation (2018) and Zhang et al. (2021), e-scooter riders strongly favored bikeways and other protected infrastructure over sidewalks and roads. In addition, reducing cars' speed limits from 55 km/h to 30 km/h in the city center of Portland was found to reduce the numbers of riders illegally guiding on the sidewalk from 66% to only 18% (Portland Bureau of Transportation, 2018). Aiming to improve the wellbeing and safety of micromobility users, and to facilitate law enforcement, ITF (2020) proposes a single speed limit of 25 km/h in all mixed-use streets.

Riding with excessive speed becomes more serious when correlated to the rider's lack of experience in handling e-scooters. The amount of data on the subject is still scarce up to this publication's date, however, a couple of studies (Austin Public Health, 2019; Nisson et al., 2020) mention the fact that many riders suffered injuries during their first ride, and in the case of Austin's study this number corresponds to 33% of them. Connected to speed is the number one cause of accidents for e-scooters: loss of balance. Blomberg et al (2019), Trivedi et al (2019), and Bloom et al (2020) report that 86%, 80%, and 49% of the accidents, respectively, were caused by the rider's loss of balance. The stability of a micro-vehicle is influenced by its design, from wheel size to frame geometry and weight distribution, which makes it more unstable than bicycles and therefore more susceptible to road irregularities and sudden falls sideways into the path of passing cars (ITF, 2020).

Understanding e-scooters riding behavior and how they interact with the riding environment is key for supporting adequate measures for better safety. Ma et al. (2021) developed a mobile sensing system to collect data related to vibrations and obstacles while riding an e-scooter and a bicycle in various types of pavements and concluded that cyclists will experience less severe vibration impacts than e-scooter riders under the same conditions. Moreover, e-scooters acceleration makes it harder for riders to have stable control of the vehicle, which poses more risk to the ride when compared to a bicycle. The scooter's simple appearance and abundant presence hide the potential for harm of a vehicle with a narrow deck, where the rider, on an upright stance, lacks the ability to properly shift its weight side-to-side, thus not being able to optimally position the center of mass (Bloom et al., 2020). Such characteristics might be one of the reasons why safety concerns are the highest, alongside costs, as shown by a couple of different studies that investigated people's motivations and barriers to the use of e-scooters (Fitt and Curl, 2019; Ceunynck et al., 2021). The risks associated with electric scooters should not be underestimated and advantages should be taken of the current transformations in urban mobility. This creates an opportunity to improve regulation for vehicle use, e.g., driving speed incompatible with injurious outcomes (ITF, 2020).

2.5. Helmet usage and legal regulations

2.5.1. Helmet usage

Helmets are perhaps the most important protective gear to wear when riding bicycles, skateboards, hoverboards, skates, e-scooters, and any other type of vehicle where the rider is a vulnerable road user. In a study by Joseph et al. (2017) that assessed the association of helmets with the severity of TBI after bicycle-related accidents, it was found that helmets reduced the probability of severe TBI and death by 51% and 44%, respectively. Similarly, Høye (2018) concluded that wearing a bicycle helmet can reduce TBI by 53%. Page et al. (2020) found a 20% TBI reduction thanks to wearing a helmet in the event of bicycle crashes. Scott et al. (2019) states that helmet use is associated with a shorter stay in hospitals or Intensive Care Units (ICU) as well as a lower risk of death.

Despite its evident importance, customers of e-scooter sharing services rarely use helmets. In fact, they are less likely than cyclists to wear helmets for both shared and private vehicle use (N. L. Haworth & Schramm, 2019).***Table 3*** summarizes the numbers reported in the literature for helmet use among e-scooter users. Helmet use is rare, ranging from 0% (Badeau et al., 2019) to just 7% (Lefrancq, 2019) in the majority of cases. Nevertheless, among the 10 studies, there is one exception. In Brisbane, Australia, helmet use among riders of shared e-scooters was reported to be 64.2% (N. L. Haworth & Schramm, 2019). The much higher percentage is probably related to the mandatory helmet use in Australia for both bicycle and e-scooter users, while in the other nine cities, helmets are not mandatory.

Table 3 - Helmet use in different cities.

Ref.	City	Type of study	E-scooter riders	Helmet use (%)
1	Salt Lake CIty, Utah (U.S.)	ED patients	50	0
2	Austin, Texas (U.S.)	ED patients	190	1
3	San Diego, California (U.S.)	Trauma patients	103	2
4	Frankfurt, Germany	Trauma patients	76	1 . 3
5	Brussels, Belgium	On-street interview	226	7
6	Auckland, New Zealand	ED's radiology	63	6 . 3
7	Los Angeles, California (U.S.)	Trauma patients	248	3
8	Santa Monica California (U.S.)	ED patients	228	4 . 4
9	Copenhagen, Denmark	EMS records	112	3 . 6
10	Brisbane, Australia	Observational	698	64 . 2

ED = emergency department ; EMS = emergency medical services

Sources: [1] Badeau et al (2019) [2] Austin Public Health (2019) [3] Kobayashi et al (2019) [4] Störmann et al (2020) [5] Lefrancq (2019) [6] Mayhew & Bergin (2019) [7] Bloom et al (2020) [8] Trivedi et al (2019) [9] Blomberg et al (2019) [10] N. L. Haworth & Schramm (2019)

The mandatory use of a helmet has a direct influence on the driver's behavior. Additionally, other relevant factors help to explain the low number of e-scooter riders wearing a helmet. In the study mentioned earlier, in Brisbane, shared bicycle services were also observed, and helmet usage by cyclists is nearly 20% higher – 81% in total. Similarly, in another observational study, in Los Angeles, shared bicycle users wore a helmet in 6.1% of the instances, whereas the e-scooter ones only in 1.8% (Sparks et al., 2019). Regardless of the low absolute percentage, which might be related with the absence of obligation by law to wear a, the difference between the two groups is significant, especially when considering that the number of e-scooter riders observed was almost six times higher than that of cyclists (1390 against 228).

The fact that e-scooters are simpler in appearance, making it easy to underestimate the potential risks, attracts more spontaneous and unprepared riders, a portion of which can be easily comprised of tourists (Bloom et al., 2020). The spontaneous nature of many e-scooter trips makes it rather impractical for riders to bring a helmet during their occasional use of a scooter (Yang et al., 2020). In addition, e-scooter trips are normally shorter than bike trips and the short commute in itself engender a belief that there is a minimal risk of injury because the scooter will be driven for a more limited amount of time (Todd et al., 2019).

Some attempts have been made by a few e-scooter rental companies to increase helmet use among their customers, like helmet giveaway campaigns (Stuff, 2018) and offering a free helmet – customer pays only the shipping costs (Bird, 2021). However, according to Constant et al. (2012), such campaigns have virtually no result. Attempts made by bike rental companies resulted in just 6.6% of helmetless users having been convinced to use one through a giveaway campaign and the impacts of the intervention completed faded within the first 5 months. These companies often use social media to advertise products and campaigns, since these platforms are nowadays a crucial way to communicate with their customers. In order to determine to which extent these e-scooter rental companies emphasize safety on Instagram, Allem & Majmundar (2019) monitored one of the largest companies in the sector – Bird – and its posts, only to find out that just 6.17% of them contained persons wearing protective gear and 1.57% mentioned protective gear in the comment box. Yet, the best initiatives seem to be coming from places where helmet use is mandatory – for instance, Brisbane – where rental companies leave some scooters with a helmet hanging on the handlebar (Abc News, 2018) to increase the convenience for the customer, and thus, facilitating and promoting its use.

Wearing a helmet for spontaneous riders can be inconvenient and costly in a few different ways: they may perceive the time and energy to get a helmet as an inconvenience itself (Todd et al., 2019); helmets have a purchasing price, requiring financial resources; and must be carried around and stored when not in use, demanding opportunity costs or access to secure storage; and even the good helmets can be uncomfortable in hot weather (Sparks et al., 2019). For some, there is also a reluctance to share a helmet publicly for hygiene reasons (Fishman et al., 2012).

Furthermore, Finnoff et al. (2001) investigated the barriers to helmet use among children, adolescents and adults. It was found that the use of helmets by peers is a major factor in the decision of wearing a helmet or not in all age groups. Adults also underestimate the risks of riding without a helmet – 72% indicated that the risk of head injury was between “none” and “moderate”. The choice not to wear a helmet can be said to be riskier than the choice to wear a helmet, because helmet use mitigates outcome variance, raising costs of good outcomes – arriving completely safe, but with the cost of minor inconvenience (hair in disarray, sweat, etc.) – and lowering costs of bad outcomes – to suffer a serious accident, but with the benefit of considerable protection from injury – (Sparks et al., 2019).

Although there is no study on the effectiveness of helmets for e-scooter driving, the findings of previous studies assessing the protective performance of helmets for other vehicles, such as motorcycles (Fernandes and Sousa, 2013; Striker et al., 2015), skateboards (Lustenberger et al., 2010), bicycles (Joseph et al., 2017; Høye, 2018) and even hoverboards (Siracuse et al., 2017), indicate that helmet use is beneficial for e-scooter riders as well. A recent commentary by (Rivara, 2019) raises the question of a new public health problem since the numbers of users and injuries are increasing, contrary to the number of users wearing a helmet. The lack of obligation to wear a helmet, the lack of testing standards that assess the effectiveness of the helmets specifically to be used with these vehicles, and the current lack of solutions from helmet manufactures are some of the steps that need to be urgently tackled with well-defined legislation and specifically designed solutions for e-micromobility users.

2.5.2. Mandatory vs. Non-mandatory use of helmets

In most countries, helmet use while driving an e-scooter is not mandatory but encouraged instead. It has already been discussed in the previous section the undoubtable benefits of wearing a helmet in case of an accident, but there is still no consensus on whether they should or should not be mandatory by law for bicycles and e-scooters. In the case of other powered two-wheel vehicles, La Torre et al. (2007) studied the implementation of the mandatory helmet law for mopeds in Rome, Italy. Helmet use increased from 5% to 95%, besides also decreasing the incidence rate of head trauma from 26.65/10.000 person-years to 8.88/10.000 person-years. Another investigation looked into the opposite situation: the removal of a mandatory helmet law in Michigan, U.S., which made the number of non-helmeted riders increase from 7% to 28% and also the fatalities involving non-helmeted from 14% to 68% (Striker et al., 2016).

In the case of e-scooters, there are no investigations depicting how a mandatory law affects the incidence of head trauma or other injuries. However, it seems that the growing number of accidents and injuries have raised some recent concerns. In South Korea, just the Samsung Fire & Marine insurance company reported five times more accidents involving e-scooters in 2018 when compared to 2016, including two fatalities. Amongst all these riders who filed the accidents report, only 12.6% were wearing a helmet (Samsung Fire & Marine, 2019). Recently, the government revised the country's Road Traffic Act, making the use of helmets mandatory for e-scooters (Neuron, 2021).

Moreover, observational studies have been conducted in both cities where helmet use is mandatory by law and where it is voluntary, and numbers are generally much lower in the latter. In London, for instance, e-scooters are currently forbidden, but there are several bike-sharing companies in place and the use of a helmet is only recommended. Goodman et al. (2014), as a result of an observational study of bike-sharing users in London, found that 16% were wearing helmets. This proportion is lower in Montreal, Canada, where only 12% were observed wearing a helmet (Tan et al., 2019). In Toronto is about 20.9% (Bonyun et al., 2012), Washington D.C 25.4% midst commuters and casual riders (Kraemer et al., 2012) and New York just 11.1% (Basch et al., 2015).

Now looking to the cities where the use of a helmet is mandatory for all ages, the percentages grow significantly. As already mentioned before, in Brisbane, Australia, N. L. Haworth & Schramm (2019) documented 61% of e-scooter riders and 81% of bike-share riders making use of a helmet. Consistent with this study, is the one by Zanotto & Winters (2017), in Vancouver, Canada, another city where using helmets is mandated by law and helmet use is about 64% among bike-sharing users. Some implications, however, have been made that vehicle share systems of cities in Australia, especially Brisbane and Melbourne, have lower ridership mainly because of the imposing laws (Fishman, 2016; ITF, 2020). Interestingly, mandatory helmet legislation was not featured at the top of the list of barriers for the use of shared micromobility in Australia. Instead, the inconvenience of one having to carry its helmet scores higher on that list (Fishman et al., 2014). In fact, in August 2011, when the Brisbane City Council distributed 400 helmets across CityCycle's fleet (the public sharing company) the short-term usage of the bikes increased dramatically (Fishman et al., 2013). Making helmets available for the public plays a relevant role in the adherence to the services by the public. In Vancouver, the public bike-sharing company, Mobi, the largest in the world, offers complimentary helmets that are attached to each bicycle in a way that users must handle them when removing the bike from the dock (Zanotto & Winters, 2017). Besides its 64% helmet use, it also has a good average of system usage – around two to three trips per bicycle per day – higher than the ones from Melbourne, Brisbane, and Seattle systems that have fewer than one trip per bicycle per day (Fishman, 2016).

Seattle is the exception among the cities where bike helmets are mandatory. Only 20% of the shared micromobility users wear helmets, which is comparable to the cities where the use is optional. Seattle is close to Vancouver, and both have similar size, similar urban forms, and the same rules for helmets, but disparate numbers regarding its use. The likely reason for this difference is that Vancouver's system, Mobi, offers helmets with the bikes, whereas Seattle's systems do not (Mooney et al., 2019). Although helmets are more frequently used if mandatory, users would be more willing to wear one if it is easily accessible. Irrespective of the helmet law, inconvenience constitutes a significant barrier to helmet use by riders of shared micromobility, be they e-scooters, bicycles, or e-bikes (Sparks et al., 2019).

2.6. Helmet regulation – standards & tests

For the helmets to be allowed into the market of a country, they need to pass a specific certification standard (Fahlstedt et al., 2021). In these certification standards, the primary metric to assess impact performance is the headform's linear acceleration measured during a drop test. Helmets are considered to have met the certification criteria if the helmeted headform acceleration is below a prescribed threshold (Cripton et al., 2014). This test is known as the impact attenuation test or shock absorbing test, and in the main bicycle helmet standards, which are the Australian/New Zealand (AS-NZS 2063), the American (CPSC 1203), and European (EN 1078), the peak linear acceleration thresholds are 250 g, 300 g, and 250 g, respectively. There are other specifications, which might be general or specific to the standard. These are discussed throughout this section. Besides the impact attenuation test, these standards have also three other tests that the helmets must comply with: positional stability, peripheral vision, and retention system strength. On top of these, the Australian/New Zealand AS-NZS 2063 has also a load distribution test that is not assessed by the other two.

These above-mentioned standards and their tests are for bicycle helmets in general, encompassing also other vehicles such as skateboards and roller skates. However, they do not distinguish between electric and human-propelled vehicles. In 2016, the Dutch bicycle industry identified the need to provide users of high-speed electrically assisted bicycles (S-EPACs) with a more suited helmet. Therefore, the NEN (refers to Dutch norm, in Dutch) consulted many stakeholders and established a project group consisting of S-EPAC manufacturers, helmet manufacturers, test institutes, among others, to put together a set of requirements for a helmet that would provide an enhanced safety level compared to the EN 1078 as a result of the higher speeds reached by the electric vehicles (NTA 8776 - Helmets for S-EPAC Riders, 2016). This effort resulted in the norm NTA 8776 in the Netherlands, which is a modified version of the EN 1078 standard consisting of significant modifications concerning the fall velocities in the impact attenuation test, that will be detailed next, and the test area of the helmet, which is larger in order to provide more protection of the temporal and occipital regions of the head. Despite being a modified version of the EN 1078 standard, the Dutch norm NTA 8776 represents a step forward towards the recognition that electric two-wheelers may demand higher levels of safety for their users.

2.6.1. Impact attenuation test

All three standards perform this test to ensure that helmets will adequately protect the head in a collision. In this test, a sample helmet is secured onto a headform, and the assembly helmet-headform will be dropped from a specified height, in freefall until it impacts a fixed steel anvil placed on the ground. The headforms used in the test are made of K-1A magnesium alloy because of its rigidity and low-resonance (CPSC 1203 - Safety Standard for Bicycle Helmet, 1998). Headform sizes follow a typical designation, A, E, J, M and O - although their dimensions are defined by different standards (see ***Table 4***). Prior to testing, the sample helmets (number of samples vary according to the standard) should be conditioned to the following environments: ambient temperature; low temperature; high temperature; and for the AS/NZS 2063 and CPSC 1203 standards, water immersion, whereas for the EN 1078, artificial aging (which includes water spraying, but not immersion).

Table 4 - Differences amongst standards

Standard	Nr. of samples (helmets)	Conditioning	Max. peak acceleration (g)	Headforms standard
AS/NZS 2063	10	AT, LT, HT, WI	250	AS/NZS 2512.1
EN 1078	4	AT, LT, HT, AA	250	EN 960
CPSC 1203	8	AT, LT, HT, WI	300	ISO/DIS 6220-1983

AT = AMBIENT TEMPERATURE ; LT= LOW TEMPERATURE ; HT= HIGH TEMPERATURE ; WI= WATER IMMERSION ;
AA= ARTIFICIAL AGEING

In the CPSC 1203, the impact tests are performed against three different solid steel anvils (flat, hemispherical, and curbstone), while in the EN 1078 they are two (flat and curbstone), and in the AS/NZS 2063 just one (flat). What mainly determines if a helmet has successfully passed the test is the peak headform acceleration during the fall, which shall not exceed 250 g for both the European and the Australian/New Zealand standards and 300 g for the American.

As for the Dutch norm NTA 8776, the fall velocities are increased for the test. On the flat anvil, the impact speed is 6.5 m/s, and on the curbstone anvil of 5.42 m/s.

The EN 1078 standard sets the speed of 5.43 m/s and 4.57 m/s for the impacts on the flat and curbstone anvils, respectively. The maximum peak acceleration remains the same, 250 g.

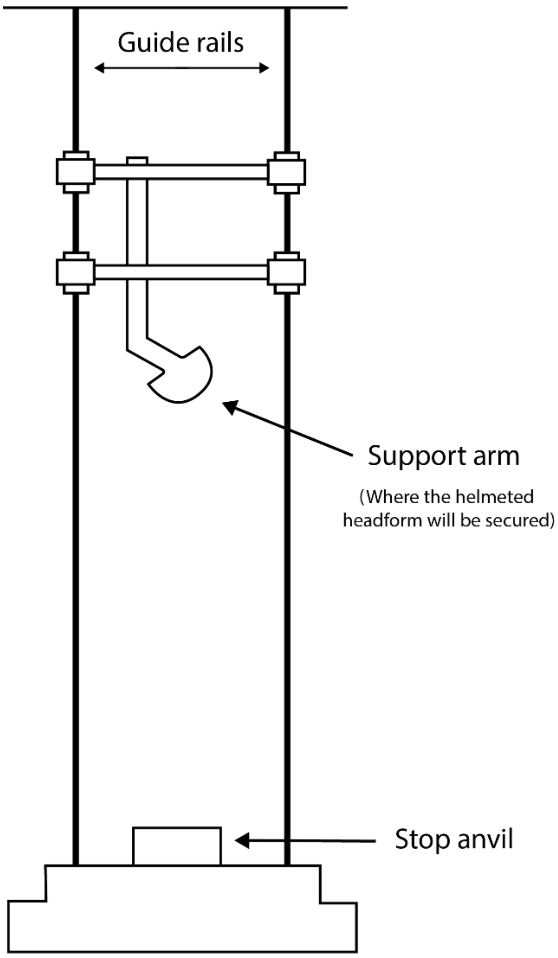


Fig. 3 - Impact attenuation test. Adapted from: CPSC 1203 Standard

2.6.2. Retention system strength

This test certifies that the chinstrap is strong enough to prevent breakage or excessive displacement that could allow a helmet to come off during an accident. The test equipment consists of a dynamic impact apparatus that allows a drop weight (4 kg, steel) to slide in a guided free fall to impact a rigid stop anvil. Two cylindrical metal bars that belong to the apparatus, distant 76 ± 1 mm from each other that spin freely, make up a stirrup that represents the bone structure of the lower jaw (CPSC 1203 - Safety Standard for Bicycle Helmet, 1998). This entire apparatus hangs freely on the helmet's retention system, and the helmet itself is attached to an appropriate headform (***Fig. 4***). The fall height is the only diverging point amongst the three standards, being 600 mm in both CPSC 1203 and EN 1078 and 250 mm in the AS/NZS 2063. The retention system shall not exceed 30 mm of elongation, measured by a displacement transducer contained in the apparatus.

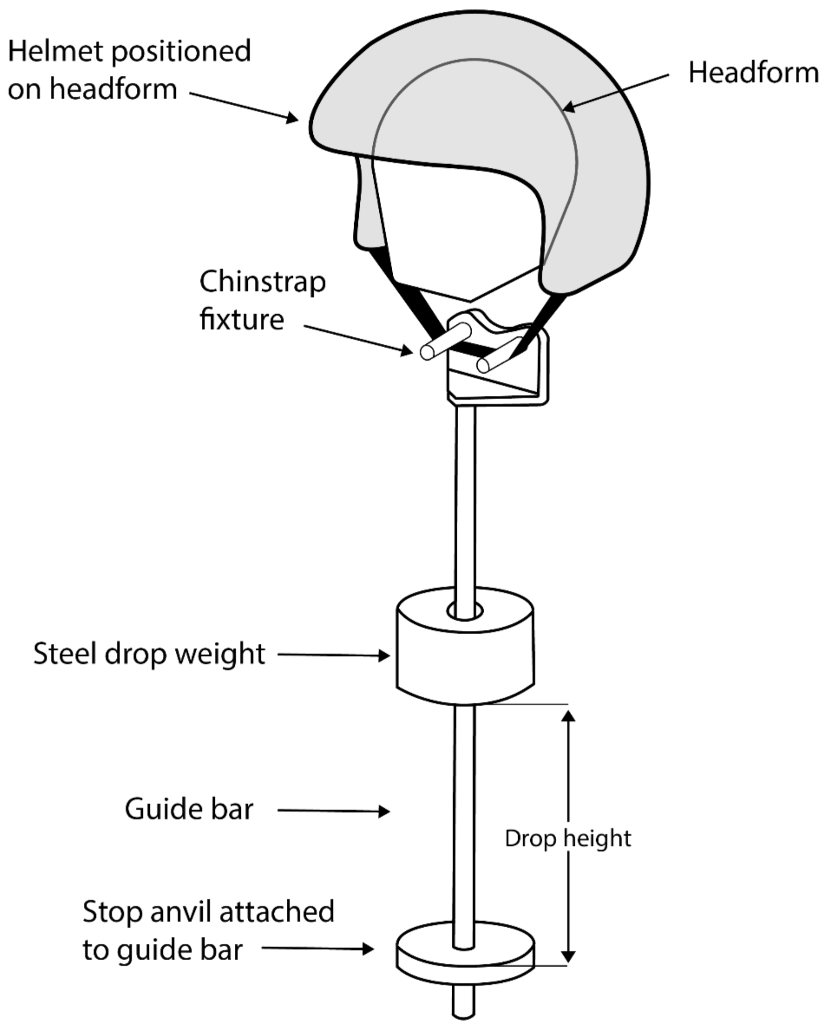


Fig. 4 - Simplified representation of the retention system strength apparatus. Adapted from: CPSC 1203 Standard

2.6.3. Positional stability test

The positional stability test (CPSC 1203) or retention system effectiveness (EN 1078), or static helmet stability (AS/NZS 2063) have different designations but the same objective, which is to verify how effective the helmet's retention system is in preventing the helmet "rolling off" from the head. However, despite having the same objective, the tests are different regarding execution. In the American norm (CPSC 1203), the headform is secured in a test fixture and rotated up to 180° with a 4 kg drop weight attached to the edge of the test helmet. In the European one (EN 1078), the headform is in an upward position fixed to a base on the ground, and a drop weight of 10 kg is hooked to the edge of the test helmet using a flexible strap and a pulley. In both tests, the drop weight is released, falling free from a height of 600 mm in the first and 175 mm in the latter until it hits a stop anvil. The American standard also demands that the test is repeated with the headform's face pointing upwards to pull the helmet from front to rear. The helmet fails both standards if it comes off the headform . A graphic representation of the CPSC 1203 and EN 1078's positional stability tests, side by side, can be seen in ***Fig. 5***.

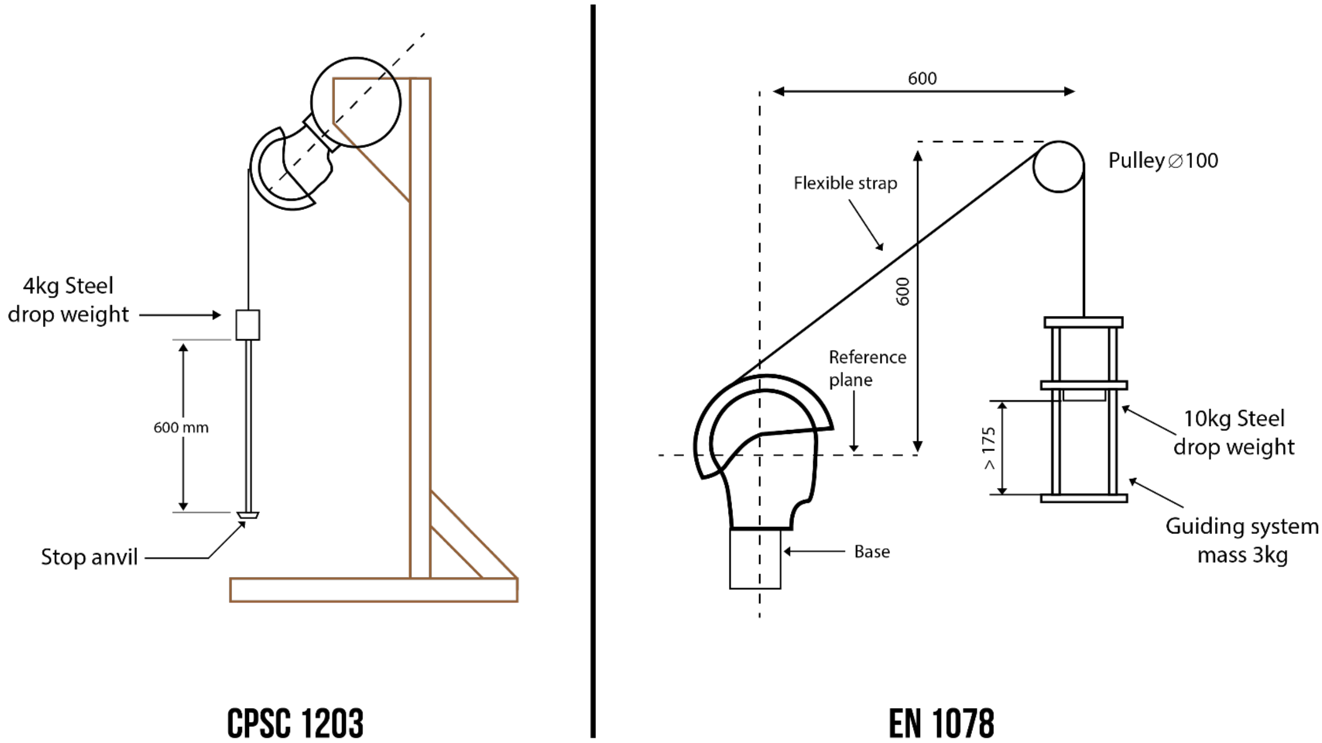


Fig. 5 - Positional Stability Test configuration of: left) CPSC 1203; right) EN 1078. Adapted from CPSC 1203 and EN 1078

2.6.4. Peripheral Vision test

The peripheral vision test checks whether the helmet allows a minimum field of vision of 105° to both left and right of the midsagittal plane (***Fig. 6***), ensuring there is no obstruction to the rider's peripheral vision.

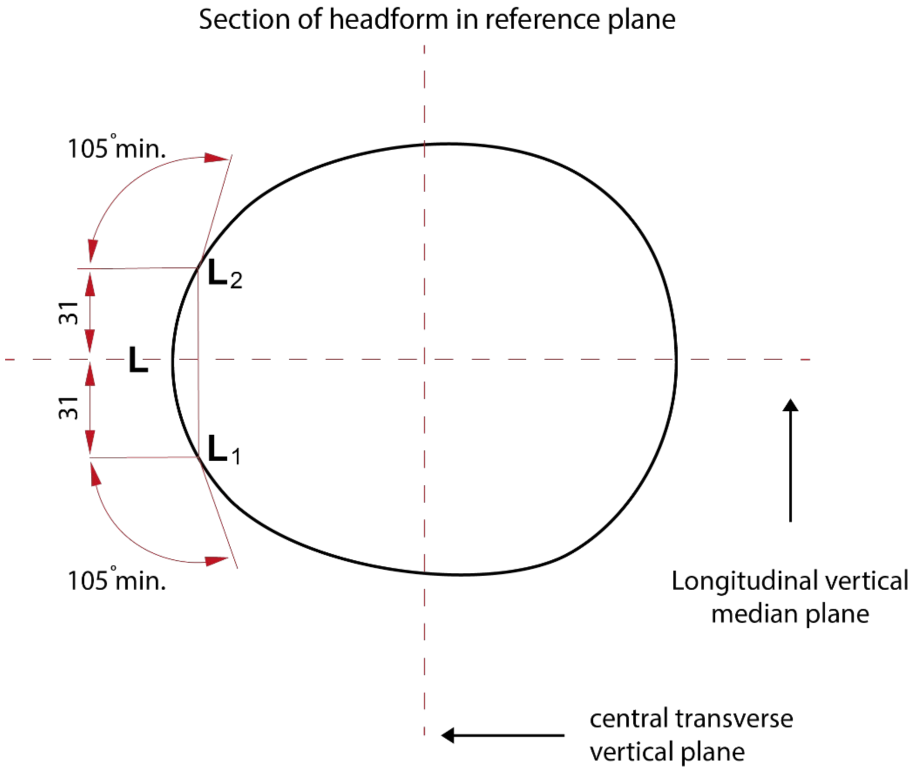


Fig. 6 - Field of view required to comply with the EN1078 standard. Adapted from: EN 1078 Standard

2.7. Products available in the market

As previously discussed, inconvenience is a significant obstacle to helmet use by riders of shared vehicles. As a suggestion to tackle this issue, Kobayashi et al. (2019) and Sparks et al. (2019) mention the collapsible and folding helmets as a way to make helmet use more feasible and convenient for occasional riders or tourists groups, which constitute a good part of the shared micromobility user's population. These types of helmets, in theory, occupy less space when not in use and could be more easily stored and transported around. The market offers some options of models ranging from 25% to 50% compression in size when collapsed.

In addition, the materials diversity is immense – from the Headkayse One's military-grade ballistic nylon (***Fig. 7***) (Hedkayse, 2021) to the Closca Fuga's Polycarbonate with reinforced fiberglass (***Fig. 8***) (Closca, 2017). Thermoplastic materials, such as high-density polyethylene (HDPE) and acrylonitrile butadiene styrene (ABS), are amongst the most used to manufacture the stiff outer shell of bicycle helmets - of any type, collapsible or not - alongside polycarbonate (PC). Their function is to distribute the impact energy over a large area, thus avoiding concentrated loads (Di Landro et al., 2002). These materials have a great performance in protecting the head against impacts, especially PC, a ductile thermoplastic resistant to penetrations (Shah, 2009), which explains why it is widely used by the industry for this kind of application..

Fig. 7 - Headkayse One helmet (Headkayse, 2021)

Fig. 8 - Closca Fuga Helmet (CLOSCA, 2017)

For the intermediate layer (protective padding), the one responsible for effectively absorbing the impact energy, thus reducing the load transmitted to the head, polymeric foams such as expanded polystyrene (EPS), expanded polypropylene (EPP), and expanded polyurethane (EPU) are normally used. The EPS is probably the most common among the foams, given its convenient cost-benefit ratio and its outstanding capability of energy absorption (Di Landro et al., 2002). However, in the context of shared micromobility, the traditional combination of these materials in the production of collapsible and folding helmets still presents two inconveniences: the first is the cost – such types of helmets usually have price tags above $100, making it an obstacle for the spontaneous riders of the shared micromobility; the second is the fact that making the helmet up to 50% smaller when not in use does not necessarily make it more convenient for the user group in focus. After all, they have not been designed for shared micromobility but private-owned vehicles instead.

It is also important to mention that the kinematics involved in driving e-scooters are different from bicycles given their upright standing position, which indicates the need for a more specific or optimized type of protection. Studies recreating accidents involving e-scooters through numerical simulation would be of great importance to assess and recognize the specific needs of protection for this application. However, as far as the author knows, there are no references dealing with finite element analysis (FEA) of e-scooter crashes.

A solution addressing the challenge of helmetless riders pose to bike-sharing came along in 2016 with Ecohelmet (***Fig. 9***), a helmet designed specifically for riders of shared micromobility that won the 2016 International James Dyson Award of design (EcoHelmet, 2017). Made of waterproofed recycled paper in a radial honeycomb pattern and being able to fold flat, Ecohelmet was a promising sustainable solution for spontaneous rides. However, for unknown reasons, the product has never reached the market. Most likely, it failed to comply with the safety standards, something that happens quite often with collapsible helmets. It was exactly the case of the Morpher helmet (***Fig. 10***), a folding helmet that did not meet the U.S.'s national safety standard and was recalled (Consumer Reports, 2020).

Fig. 9 - EcoHelmet (EcoHelmet, 2017)

Fig. 10 - Morpher helmet (Consumer Reports, 2020)

2.8. Existing solutions for shared micromobility

There are very few solutions in place addressing the issue of helmets for shared micromobility. One of them, already mentioned earlier, comes from the Canadian public bike-sharing company "Mobi". Each of their bicycles is equipped with a complementary helmet (***Fig. 11a***) and the system was designed in such a way that the rider must handle the helmet when removing a bicycle from the dock (Zanotto & Winters, 2017). Such a system proved to work well on docked systems, and it is one of the factors that contributed to the high percentage of helmet use in the city of Vancouver. However, for completely dockless systems, which are the great majority of the e-scooter sharing services, this solution cannot be applied since it relies on the vehicle-dock interface to exist. In the case of dockless vehicles, the system would have to be embedded in the vehicle itself, and, at the moment, three companies recently invested in this type of solution.

In September 2019, "Hopr", a U.S. based bike and e-scooter sharing company, announced the launch of their newly developed helmet – METRO™ – that was designed for micromobility, being the first of its kind (Hopr, 2019). The helmet, similar to the one deployed by “Mobi”, has a small hole on its top, through which a metal cable passes and locks itself on a device attached to the e-scooter (***Fig. 11 b***).

On a more technological and integrated approach, the company “TIER” from Germany developed a built-in smartbox for their e-scooters, which contains a foldable helmet inside (***Fig. 11 c***). Furthermore, the box, unlocked through the application, also contains some hairnets, which are replaced every time the battery of a scooter is swapped. The helmet complies with the EN 1078 standard and is subject to quality control every five rides (TIER, 2020).

Also having an integrated helmet solution, but for a different type of vehicle, the American company “Wheels” developed their smart helmet system (***Fig. 11 d***) specially built for their micro-vehicle that lies somewhere between a bicycle and a scooter. The elegant solution features a built-in sensor to detect if the helmet is in use, the ability to unlock the helmet through the smartphone application, and a removable liner made out of a biodegradable material (Wheels, 2020).

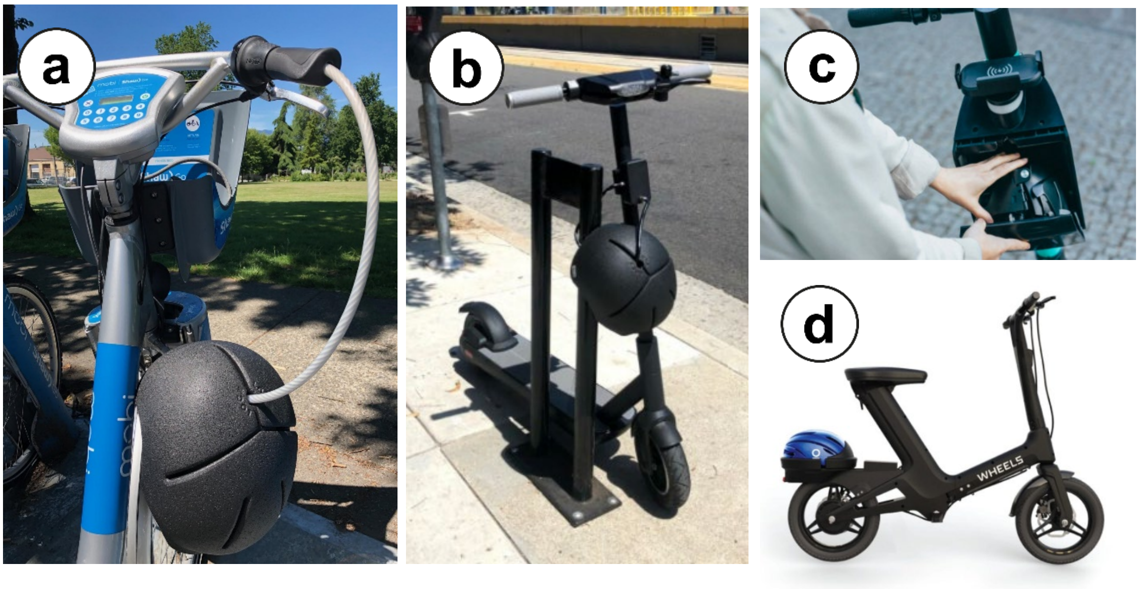


Fig. 11 - Helmet solutions for micromobility: a) Mobi bicycle with complementary helmet (Mobi, 2019) *; b) Hopr's system (Hopr, 2019); c) TIER's smartbox with foldable helmet (TIER,2020)); d) Wheels' vehicle with integrated helmet system (WHEELS, 2020)*

Another emerging solution trying to promote the use of helmets is what is called the ’helmet selfie’. The technology is application-based and works in a couple of different ways: some companies, like ’Bird’, ask their users to take a selfie through the application by the end of each trip. An image classifier AI can detect if the user is wearing a helmet and the ones who demonstrate helmet usage will be rewarded with future travel credits (Bird, 2019b). Similarly, some other companies, like ’Voi’, use the same helmet detection technology, but instead of asking for the ’selfie’ by the end of the ride, it asks at the beginning (VoiScooters, 2020). However, such features do not stop helmetless users from riding the vehicle. It is a simple way of trying to stimulate helmet usage through rewards.

2.9. Discussion and Conclusions

The recent phenomenon of shared micromobility, especially the e-scooters that were only introduced in 2017, presents many challenges since its impacts on public health and urban mobility have not yet been fully understood. More studies regarding the shared e-scooters user types (commute, recreational, occasional, frequent) and their respective behaviors must be carried out in order to properly develop solutions based on the audience and their needs. Nevertheless, in the last couple of years, some efforts have been made to increase riders’ safety and convenience, for instance, by providing integrated helmets on vehicles. Unfortunately, probably due to their recent debut in the market (the first to be announced was Hopr’s METRO™ helmet in September 2019), there are still no reported data about their use and acceptance by the public.

Beyond the challenges faced by the shared micromobility industry itself, there are also imminent challenges faced by humanity. Climate change might be the greatest of them all and the development, manufacturing, and implementation of goods and services have a direct impact on the planet, creating a pressing need to transition to more sustainable socio-technical systems (Geissdoerfer et al., 2017). From this need arose the United Nations' 2030 Agenda for Sustainable Development that, amongst its seventeen goals, has sustainable industrialization, consumption, and production patterns as priorities for the decade (Transforming Our World: The 2030 Agenda for Sustainable Development, 2015). When it comes to the manufacturing of helmets, there is plenty to be done to align the industry with the UN's 2030 agenda. Most helmets have a hard plastic shell, a foam liner, and also nylon, polyester, or polyethylene straps. Individually some of the materials can be recycled, although hard plastics like PC and ABS, which are the most used in helmets' shells, are not as easy and as widely recycled as other plastics such as HDPE, PET, and PP. However, the main problem, most of the time, lies in the way the different materials are bond together.

The helmet's liner, i.e., the polymeric foam, is molded with high-pressure steam, causing the beads expansion inside the mold. In many cases, the thermoformed hard plastic shell is placed inside the mold (in-molded), bonding the shell to the foam during its manufacturing. This process makes it difficult for the helmet to be later disposed when it reaches the end of its lifecycle because the different materials must be separated from each other in order to be recycled. The circular economy is a popular concept that plays an important role in product development. Most importantly, the product lifecycle – how it will be reused, recycled, or reintroduced in the market after its disposal are important aspects to bear in mind during its design. As defined by the Ellen MacArthur Foundation (2017), the circular economy is "a framework for an economy that is restorative and regenerative by design".

The material selection criterion is also important when considering the circular economy and a fundamental aspect concerning the UN's 2030 agenda. Materials such as the foams used for the protective layer of the helmet are quite hazardous for the environment since they take several hundred years to decompose, besides being frequently discarded after their use, consequently generating a significant amount of waste (de Oliveira et al., 2019). The reason behind the fast disposal of the material is mainly due to its vast use in the packaging industry. Nevertheless, in the case of helmets, EPS only performs well on the first impact, offering minimal protection in subsequent impacts as it deforms permanently (F. A.O. Fernandes et al., 2015). Its ductile nature leads the helmet manufacturers to recommend their disposal after it receives the first impact since it can no longer have the same mechanical behavior afterward. Such properties can be enhanced with more sustainable materials. In a study from Varela et al. (2020) where they compared the impact performance of agglomerated cork against three other commercial headbands made with synthetic foams, the results showed that the eco-friendly material provided comparable and even better performances than the synthetic ones.

Beyond the foams, replacing other fossil fuel-based plastics with more sustainable alternatives such as bio-based plastics (corn-based and sugarcane-based) is shown to play an important role in greenhouse gas mitigation (Zheng & Suh, 2019). Not only would it reduce the carbon footprint but would also reduce the hazard that some of the fossil fuel-based plastics represent when of their use and disposal. According to a study by Lithner et al. (2011), plastics such as PC and ABS, which are the most used as helmet´s outer shell, rank as one of the most hazardous plastics – position 19 and 10, respectively, out of 55 – due to the chemicals derived from non-renewable crude oil used during production.

Another key aspect of sustainability is the energy efficiency of manufacturing processes. The large-scale production of plastics through injection molding is very inefficient in terms of energy. The injection molding machines waste significant amounts of energy during the production process, emitting circa 1.67×10^8 tons of CO_2 every year globally, which seriously deviates from the requirements of cleaner production (Yang et al., 2020). Cleaner production could be achieved in many ways, such as by using renewable energy sources. However, switching to natural materials could mean a greater step towards a more sustainable and circular economy and, by simplifying the manufacturing methods, potentially reduce the cost of the final product. The latter is strictly related to the problem of low helmet use in shared micromobility since the prices of existing collapsible and foldable helmets are a big obstacle for the spontaneous rider and also a barrier for micro-vehicles sharing companies to implement an economically viable integrated helmet solution. An optimum solution must meet the needs of the user (convenience, comfort, hygiene and safety), of the company (viable cost, and implementation), and crucially, comply with the safety standards.

In most cities around the world, there is a limit defined by law on how fast an e-scooter can be ridden and, as in the state of California (California Legislative, 2018), this limit is usually 25 km/h. However, as seen previously in this article, this is entirely dependent on the legislation of the city/country, which, for instance, can be confusing or inexistent for e-scooters. The lack of regulation can lead to perilous scenarios since some of these self-balancing vehicles can ultimately exceed 32 km/h (Unagi, 2021). To better put the risks into perspective, a study using FEA to simulate the risk of brain injury for electric self-balancing scooter's (commonly known as Segway) riders when in a collision against a motorized vehicle, concluded that riding at a speed of 4 m/s (14.4 km/h) and crashing with a vehicle at 15 m/s (54 km/h) could increase the risk of serious brain injury by almost 40% when compared to lower speeds (Xu et al., 2016). It illustrates the dangers involved in riding an electric self-balancing two-wheeler vehicle and how important it is to wear a helmet to minimize the risks of having a severe TBI. Given the higher risks that come along with electric vehicles higher speeds, it could be reasonable to have in the bicycle helmet standards a specific set of safety requirements for helmets intended to be used with electric vehicles, following the example of the Dutch norm NTA 8776. One of these requirements could be to perhaps include tests regarding rotational acceleration, which is generally accepted among the researcher community as the main mechanism of brain injury (Fernandes and Sousa, 2015). Amongst the norms reviewed in this paper (EN 1078; CPSC 1203; AS/NZS 2063:2008), there is no assessment to this type of injury in their helmet impact tests. In addition, it is of extreme importance that e-scooters are regulated with clear rules indicating how to use them in the cities. Mandatory use of helmets might be a supporting solution to help increase helmet use, as long as the vehicle sharing companies provide the helmets for their riders.

There are many factors associated with the recent increase in accidents and injuries involving e-scooters worldwide, making it a rather complex problem. To properly address the issue, initiatives must be taken from multiple directions and elements: from lawmakers, through helmet manufacturers, all the way to shared micromobility companies and riders. The fact that this is a recent phenomenon, and its impacts are just starting to be understood, is a push for groundbreaking solutions that will have a positive impact on a multitude of dimensions.

The information contained in this state-of-the-art section can be visualized in an article by the author itself that has been published in the journal Accident Analysis & Prevention (Serra et al., 2021).

3. Dynamic impact tests: testing shock absorbing materials

The ability to resist impacts, whether from falling objects or head-on collisions, is perhaps the most important feature of a helmet. The protective padding, usually made from soft materials like the foams discussed in the previous topic, is the responsible for serving as a cushion for the head, decreasing the magnitude of the force coming from an impact. By deforming at low loads, the cushion limits the transmitted force (Rice et al., 2020).

However, their efficiency is compromised after only one impact, and they can no longer guarantee the same levels of protection.

In the last decade there has been some advancements in the development of impact resistant materials being used in a big range of applications that goes from sports (American football, Rugby) to military (armors and protective suits). One of these materials, the so called shear thickening fluid (STF), is a fluid that increases its viscosity under loading and has been widely used as a surface treatment to enhance penetration resistance (Gürgen, 2018). It has also demonstrated great potential to enhance impact performance when used as an interfacial element in a multi-layered structure of cork laminates, reducing up to 36% the maximum impact force (Gürgen et al., 2021). However, the shear thickening property itself is not the greatest asset of this fluid, but instead the ability to spread the load transfer over a wider area in fabric based protective systems through the increase in friction along fabrics, resulting in a lower penetration depth (Gürgen et al., 2017).

The Portugal-based company Polyanswer® has some solutions in which the STF is used as an impregnation agent and also as part of different polymers' composition. Some samples of such materials were provided to be tested for dynamic impacts of both low and high energy, which will be discussed next.

3.1. The Samples

The materials provided by Polyanswer® were of four different kinds: a 3.3 mm thick red PVC sheet; a polyurethane (PU) foam in sheets of 3, 6 and 10 mm; a sheet of 3D fabric impregnated with STF; and the shear thickening fluid itself in bulk (in a can). The red and black sheets of polymer contain a non-specified amount of STF in its composition. In ***Fig. 12*** it is possible to see one sample of each material placed on top of a piece of cork agglomerate.

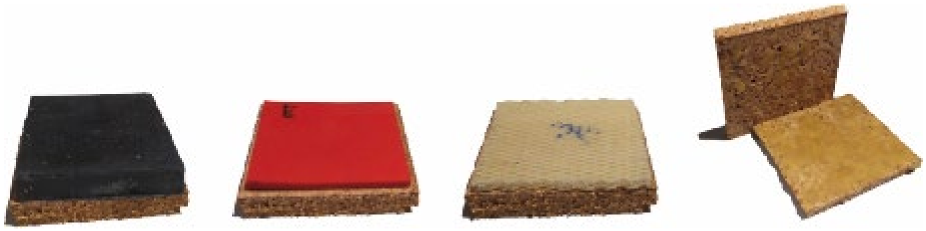


Fig. 12 - Polyanswer's samples. From left to right: 10mm thick PU foam; 3.3mm red PVC; impregnated fabric; STF spread over cork

All the samples are placed on a piece of cork agglomerate of about 180 kg/m^3 (ref. 8003 from Amorim Cork Composites) to undergo the drop impact tests. This step is necessary because the Polyanswer® sheets are not thick enough to absorb the impact energy, which could lead to a collision between the impactor and the metal base where the samples are placed on and potentially damage the equipment. A table with the different test configurations will be presented further ahead.

3.2. Dynamic impact test apparatus and settings

The equipment used for the dynamic impact tests is a drop tower located at the Department of Mechanical Engineering (DEM). A drop impact test is the most appropriate type of mechanical test to characterize the behavior and properties of the materials' samples, as their intended application will require them to function as energy absorbing agents for impact energy levels as high as 100 J. Through the data obtained from the drop tower's encoder, which measures the displacement, and from the load cell, that measures the force, it is possible to obtain the stress-strain curve of the analyzed material and determine its behavior for the desired levels of impact energy.

As represented in ***Fig. 13***, the total mass of the system, which includes the stainless-steel impactor, the load cell, and the cylindrical rod, is 20 kg. The samples are centered on the surface of a metal anvil, and they are all cut to sizes smaller than the impactor's diameter (130 mm) so that it is guaranteed that the impact energy is being applied to the whole surface area. To perform the test, the rod should be raised to the desired height and once released it will fall free vertically (only one degree of freedom) to hit the sample. During the fall the encoder will measure the displacement of the system and at the moment of impact, the load cell will register the force. Both devices convert the measurements into an electrical output signal, which will be read by a specific software and ultimately outputted in conventional measurement units –newtons (N) for force and millimeters (mm) for displacement.

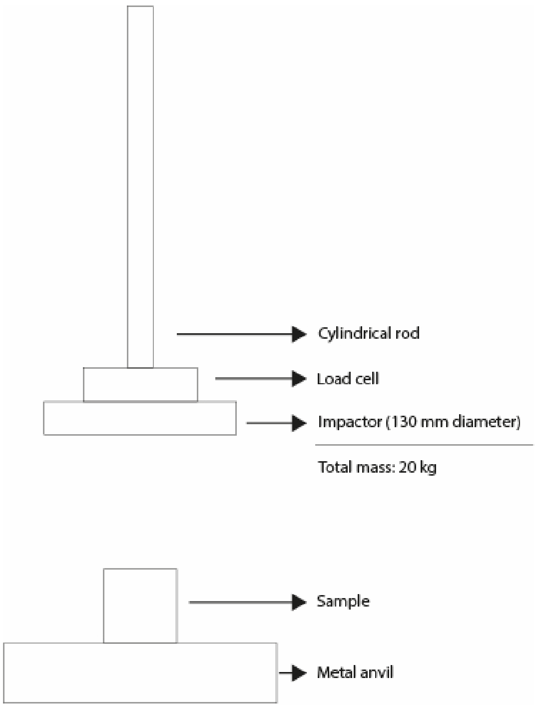


Fig. 13 - Graphical representation of the drop tower

Due to some minor vibrations at the moment of impact, the outputted force values measured by the load cell come out with some noise (Fig. 14***a***), interfering with the post-processing of all the data. To deal with this issue, a Butterworth filter was applied to the raw data in Excel® as suggested by the author of a previous study done with the same drop tower (Marques, 2016). A cut-off of 100Hz was found to work best in this situation.

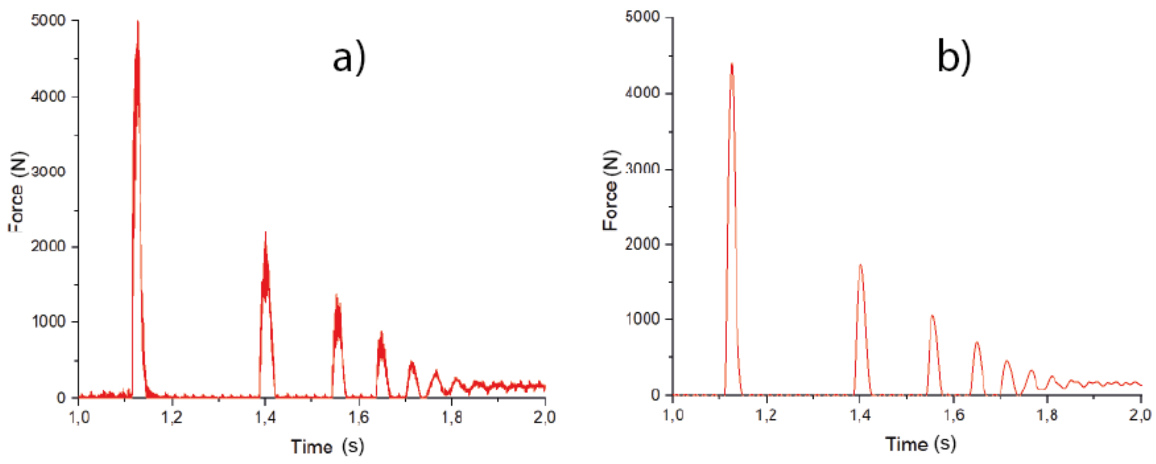
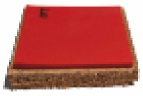


Fig. 14 - a) Example of noisy data before applying the filter; b) Smoothed out data after applying the Butterworth filter with 100Hz cut-off

3.2.1. Settings for the 20 J impact tests

At first, low energy impact tests – 20 J – were performed. For this amount of energy to be transmitted at the moment of impact, the drop tower was raised to a height of approximately 103 mm (measured from the sample's top surface to the impactor's bottom surface). The samples, which includes the Polyanswer's materials and the sheets of cork agglomerate, were all cut to pieces of approximately 50x50 mm (some variations occurred and the exact surface area of each sample will be specified at the following results section) and combined in different ways, as can be seen in ***Table 5*** alongside their description and respective code that will be used as referral when discussing the results.

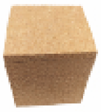
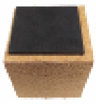
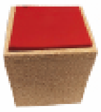
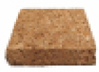
Table 5 - Samples' code and composition for the 20 J impact tests

Sample's photo	Composition	Code
	2 x 5 mm cork with STF in between	C5 - F - C5
	2 x 5 mm cork	C5 - C5
	1x 10 mm cork + impregnated fabric	C10 + TI
	1x 10 mm cork	C10
	1x 10 mm cork + 1x 3.3 mm PVC	C10 + PVC
	1x 10 mm cork + 1x 3.3 mm PU foam	C10 + BP 3.3
	1x 10 mm cork + 1x 10 mm PU foam	C10 + BP 10
	1 x 10 mm PU foam	BP 10
	1 x 20 mm cork (hexagon shaped)	C20
	1 x 20 mm cork + TPU cover	C20 + TPU
	1 x 20 mm cork + TPU cover + STF in between (encapsulated)	C20 - F - TPU

3.2.2. Settings for the 100 J impact tests

After the low energy impact tests, high energy ones of 100 J have been performed. For this setting, the impactor's surface was approximately 510 mm distant from the sample. The same combination schemes were made, differing only in the dimensions, especially the thickness of the cork agglomerate samples, given that the impact energy is five times higher than the previous tests, therefore making necessary the use of thicker samples to avoid the collision between the impactor and the anvil. In ***Table 6***, the combinations for the high energy impact tests are represented.

Table 6 - Samples' code and composition for the 100 J impact tests

Sample's photo	Composition	Code
	1 x 60 mm cork	C60
	1 x 50 mm cork + 1x 3.3 mm PU foam	C50 + BP 3.3
	1x 60 mm cork + 1 x 3.3 mm PVC	C60 + PVC
	1x 60 mm cork + impregnated fabric	C60 + TI
	1x 50 mm cork + 1x 10 mm cork with STF in between	C50 - F - C10
	1x 30mm cork	C30
	1x 30mm cork + TPU cover	C30 + TPU
	1x 30mm cork + TPU cover + STF in between (encapsulated)	C30 - F - TPU

3.3. Results

3.3.1. 20 J drop impact tests

To undergo the impact tests, three samples were made for each of the combinations represented in ***Table 5*** so that the test could be repeated three times to ensure that the results would be consistent. In case all three samples presented virtually the same result (with insignificant levels of variation), only one would be considered and kept for further analysis, and if one result would greatly differ from the other two, it would get discarded. The selection criterion was based on which had the best relationship between 'the second and the fist force peak ('Peak 2/ Peak 1'), since this analysis defines how much energy was dissipated during the impact.

Table 7 - Panorama of the data related to the 20 J drop tests

Combination code	Total mass	Mass of fluid (STF)	Thickness	Area of impact	Peak 1	Peak 1 duration	Peak 2	Peak 2 duration	Peak 2/ Peak 1	Max. σ	Max. ε	Max. acceleration
	(g)	(g)	(mm)	(mm²)	(N)	(ms)	(N)	(ms)		(MPa)	(%)	(g)
C5 - C5	4,8		10	2601	4097	19	1472	23	0,359	1,57	42,1	25,75
C5 - F - C5 (1)	9,2	4,34	10,7	2601	4022	20	1495	24	0,371	1,55	36,31	24,03
C5 - F - C5 (2)	5,76	1,72	10,1	2704	4115	19	1535	23	0,373	1,52	37,61	25,52
C5 - F - C5 (3)	9,72	4,76	10,8	2500	4023	19	1467	23	0,364	1,61	27,69	23,61
C10 + TI	5,8		14,15	2495	3790	23	1107	30	0,292	1,52	50,13	21,64
C10	4,34		9,65	2588	4272	18	935	32	0,218	1,65	76,32	30,55
C10 + PVC	13,76		12,95	2657	4015	20	1066	41	0,265	1,51	48,36	23,87
C10 + BP 3,3	12,94		12,95	2076	3510	23	976	32	0,278	1,69	49,25	22,27
C10 + BP 10 (1)	14,48		20	2421,4	2566	32	591	54	0,23	1,05	44,32	15,05
C10 + BP 10 (2)	15		20	2590,8	2473	39	601	51	0,243	0,95	42,86	14,89
C10 + BP 10 (3)	15,26		20	2478,6	2523	40	689	46	0,273	1,01	41,94	16,38
BP 10	9,62		10	2570	5339	15	848	42	0,158	2,08	65,58	31,07
C20 + TPU	9,54		21	1043	2284	43	802	50	0,351	2,19	34,97	14,55
C20	4,2		19	1031	2316	39	558	58	0,218	2,46	53,5	13,2
C20 - F -TPU (1)	12	2,14	22,9	1043	2456	32	792	49	0,322	2,55	35,13	14,63
C20 - F -TPU (2)	9,48	1,26	21,3	1043	2096	36	770	48	0,367	2,01	42,86	12,96

The selected results and their respective data retrieved from the tests are all listed in ***Table 7***. It is important to notice that some of the combinations have more than one sample represented in the results – characterized by the number between brackets after the combination code – and that is either because the different samples had distinct properties, such as bigger amounts of STF, which is the case of the "C20-F-TPU" and "C5-F-C5" samples, or because there were significant differences amongst the collected data ("C10+BP10" samples, for instance).

Starting by comparing samples with 10 mm thickness, it is possible to notice that amidst the ones without the addition of STF (i.e., "C5-C5", "C10" and "BP10"), the "C5-C5" has a great performance regarding the first peak force (***Fig. 15a***) and maximum acceleration (***Fig. 15b***), especially when compared to the "C10", which is exactly the same cork agglomerate with the same properties but in a single piece of 10 mm. However, both the "C10" and the "BP10" perform considerably better when it comes to dissipation of energy between the first and second impact (***Fig. 16***), meaning that they can greatly reduce the magnitude of the second peak force in relation to the first.

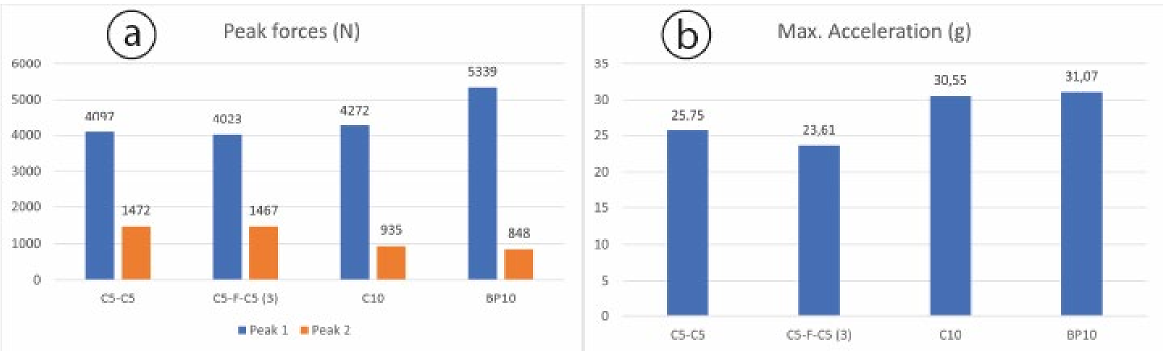


Fig. 15 - Comparison of 10 mm samples: a) Peak forces; b) Maximum acceleration

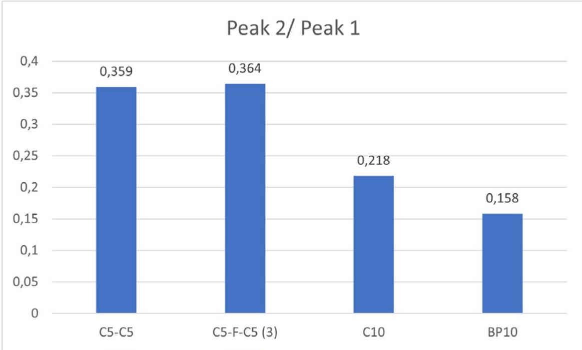


Fig. 16 – Relationship between the second and first peak forces of 10 mm samples

Looking one more time into the values of acceleration, which is an important metric to evaluate possible damages resulting from an impact, one can note that the sample with the shear thickening fluid ("C5-F-C5") is the one that performs the best, having an 8.4% reduction compared to the "C5-C5" and 22.8% to the "C10". Although the presence of the fluid did not necessarily reduce the impacts' peak forces, it does nonetheless demonstrate a potential for this type of solution to be used in combination with cork in applications where the peak acceleration needs to be limited, as is the case of helmets.

By analyzing the samples consisting of cork combined with other Polyanswer® materials, another interesting observation can be deducted: the impregnated fabric (C10+TI) has a good balance between all the evaluated properties. It not only outperforms the two others concerning the peak acceleration (***Fig. 17a***), but also is second in the force peaks indicator (***Fig. 17b***). Even though its *peak 2/peak 1* relationship is not the best amongst the three samples (***Fig. 18***), the number does reflect a good performance with 70.8% of the energy being dissipated after the first impact. Moreover, the fabric is a very light-weight material and, combined with the 10 mm piece of cork, weights only 5.8 grams. As a comparison, the second lightest material (excluding the cork alone), the "BP10", is 65% heavier than the fabric, weighting 9.62 g, and the heaviest, the "C10+PVC", is 237% heavier (***Fig. 19***). With only 1.46 g more than the

"C10" sample, the impregnated fabric offers 11.3% reduction in maximum impact force (***Fig. 20a***) and 29.1% in peak acceleration (***Fig. 20b***).

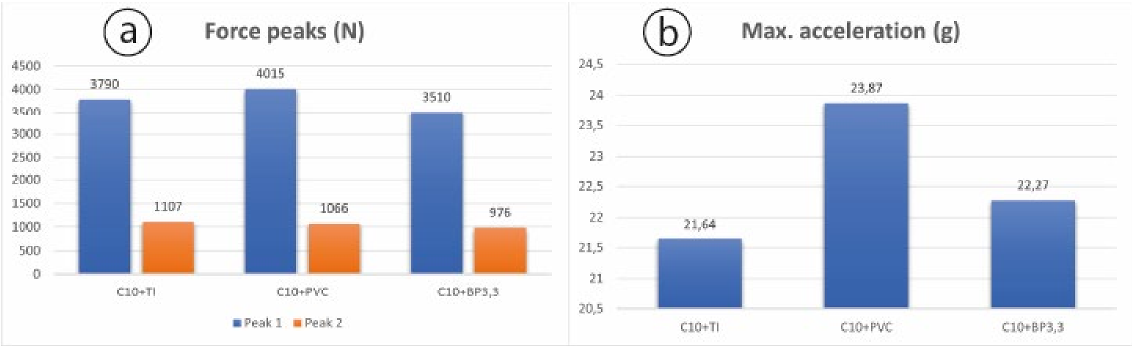


Fig. 17 - Comparison of samples combining cork with a variety of Polyanswer® materials: a) Peak forces; b) Maximum acceleration

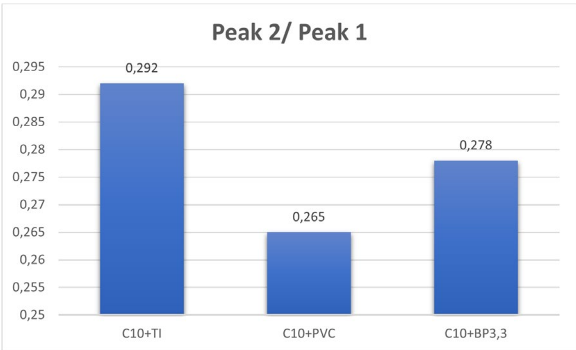


Fig. 18 - Relationship between the second and first peak forces of "C10+TI", "C10+PVC" and "C10+BP3.3" samples

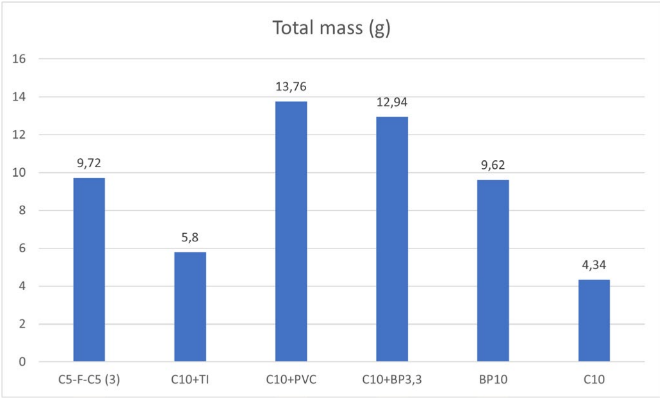


Fig. 19 - Total mass comparison between the tested samples

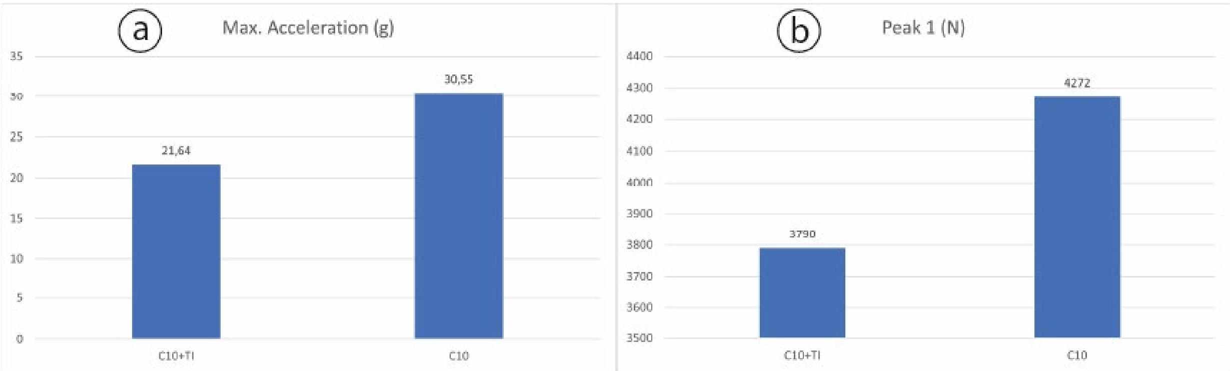


Fig. 20 - "C10+TI" performance compared to "C10": a) Max. acceleration and b) First peak force

The following battery of low-energy impact tests was conducted with samples containing Thermoplastic Polyurethane (TPU) and STF. The intention was to encapsulate the fluid, spread over the cork's surface, with a TPU cover and examine how this particular configuration would compare to the rest. As shown in ***Fig. 21a***, the encapsulated fluid ("C20-F-TPU") makes a difference in relation to the peak forces, specially the first one, reducing it by 9.5% when compared to the cork sample alone ("C20"). Additionally, the fluid does seem to also have a positive impact on decreasing the peak acceleration in all tested configurations for low-energy impacts – from the previously discussed "C5-F-C5" sample, which had a 22.8% reduction compared to the

"C10", to this encapsulated one that had 11% less acceleration (***Fig. 21b***) in comparison to its equivalent configuration, but without the fluid ("C20+TPU").

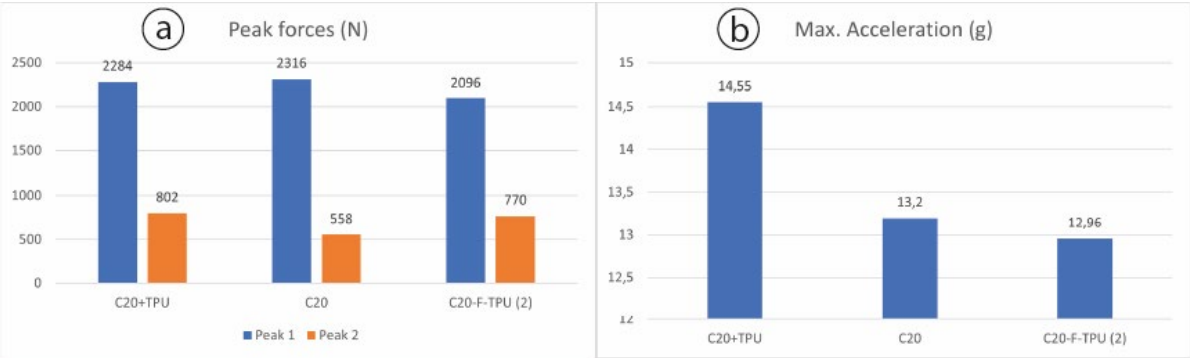


Fig. 21 - Performance of samples containing TPU and STF: a) Peak forces and b) Maximum acceleration

Overall, the impregnated fabric and the shear thickening fluid had the best performance amongst all the tested samples, proving to be promising materials for applications such as crashworthiness and shock absorption. Furthermore, the results for the STF as reinforcement, incorporated as an interlaying agent between agglomerated cork laminates ("C5-F-C5"), subject to low-energy impacts are in accordance with another study where a similar configuration (STF in between cork) was tested with various number of layers at up to 15 J impact energies, concluding that the STF improves the cork agglomerate's shock absorption performance when used in a multi-layered scheme (Gürgen et al., 2021).

3.3.2. 100 J drop impact tests

The drop tests performed on bicycle helmets safety standards consist of high-energy impacts. The European EN 1078 requires the impact velocity to be of $5.42^{+0,1}$ m/s on a flat anvil. The headform of size J, which is the medium size, used in the test is from a k1a magnesium alloy and weights 4.7 kg. Using the ***equation 1*** it is possible to obtain the kinetic energy at the moment of the impact, which is about 69 J. As for the American CPSC 1203, the impact velocity should be of 5.44 m/s and the drop assembly weight of 5 kg. In this case, the resulting kinetic energy is 74 J.

Equation 1 - Kinetic energy at the moment of impact

$$K = \frac{m \cdot v^2}{2}$$	K = Kinetic energy m = Mass of the object v = impact velocity

However, in real-life situations the impact velocity can surpass the values required for the helmet safety standards since the e-scooters can, in most places, legally reach the speed limit of 25 km/h (about 6.9 m/s), which would translate to an impact energy of about 111 J under the conditions of the EN 1078 norm. Therefore, it was decided to execute the drop impact tests in energy levels that go beyond the ones established by the norms and approximate to what could occur in real-life situations close to the maximum allowed speed for e-scooters, setting the impact energy to 100 J. This amount of energy in this particular drop tower, where the drop assembly weights 20 kg, means that the drop height should be of about 510 mm (***equation 2***).

Equation 2 - Equation for the potential energy

$$U = m \cdot g \cdot h$$	U = Potential energy m = Mass of the object h = Drop height g = Acceleration = 9.81m/s²

The same methodology from the low-energy impact tests was used, implying that there were three samples for each of the combinations represented in ***Table 8*** and that in case all three presented virtually the same result, only one would be considered and kept for further analysis and comparisons.

Table 8 - Panorama of the data related to the 100 J drop tests

Combination code	Total mass	Mass of fluid (STF)	Thickness	Area of impact	Peak 1	Peak 1 duration	Peak 2	Peak 2 duration	Peak 2/ Peak 1	Max. σ	Max. ε	Max. acceleration
	(g)	(g)	(mm)	(mm2)	(N)	(ms)	(N)	(ms)		(Mpa)	(%)	(g)
C60 (1)	44,66		60	3480,75	4417	38	1738	44	0,393	1,26	35,53	28,65
C60 (2)	46,6		60	3516,45	4480	35	1817	43	0,405	1,27	33,83	27,09
C60 + BP3,3 (1)	50,86		63,3	2461,87	4457	35	1773	47	0,397	1,81	34,66	27,74
C60 + BP3,3 (2)	53,54		63,3	2535,11	4663	36	1924	38	0,412	1,84	33,32	29,19
C50 + BP10 (1)	46,28		61	2590,8	4257	40	1455	47	0,341	1,64	41,74	25,08
C50 + BP10 (2)	45,06		61	2421,4	4279	46	1434	46	0,335	1,76	41,78	26,67
C50 + BP10 (3)	46,1		61	2478,6	4280	49	1451	50	0,339	1,72	41,6	26,83
C60 + PVC (1)	52,98		63,3	2142	4287	41	1667	41	0,388	2	34,76	25,9
C60 + PVC (2)	50,02		63,3	1911	4210	32	1197	58	0,284	2,2	36,05	25,27
C60 + PVC (3)	50,9		63,3	2075,7	4201	43	1499	51	0,356	2,02	35,19	26,36
C60 + TI (1)	43,34		64,5	2400	4170	39	1605	41	0,384	1,73	39,13	25,53
C60 + TI (2)	43,66		64,5	2488,8	4191	39	1621	43	0,386	1,68	38,53	25,31
C60 + TI (3)	45,86		64,5	2434,1	4395	38	1730	45	0,393	1,8	37,49	28,34
C50 - F -C10 (1)	47,94	4,26	61,5	3568,5	4323	38	1667	39	0,385	1,21	36,02	27,16
C50 - F -C10 (2)	47,72	4,1	61,2	3521,1	4318	38	1698	39	0,393	1,22	35,39	26,67
C30	22		29,8	3509	7150	27	2020	33	0,282	2,03	51,08	45,68
C30 + TPU	30		31	3532	7530	27	1994	34	0,264	2,13	52,83	47,58
C30 - F -TPU (1)	39	9	33	3636	7358	26	2022	33	0,274	2,02	49,07	42,85
C30 - F -TPU (2)	41	10	34,5	3556	6961	27	1951	32	0,28	1,95	46,49	39,45

The first set of analysis involves the 60 mm solid cubes of cork (“C60[1]”, “C60[2]”), samples consisting of a 50 mm cube of cork with a 10 mm thick PU foam (“C50+BP10”) and others with STF as an interlayer agent between a 50 mm and a 10 mm pieces of cork (“C50-F-C10”). All the mentioned samples have about the same thickness (with only minor variations), thus being in good terms for comparison. When looking into the peak forces, the “C50+BP10” samples demonstrate to perform better than the others, reducing the maximum impact force in up to 5.2% when compared to the “C60” samples (***Fig. 22a***). Regarding the peak acceleration, it also has the best performance amongst all, proving to decrease the values in up to 12.5% (comparing the best performing “C50+BP10” sample with the worst performing “C60”). Moreover, the PU foam has the best ratio between the first and second impact forces, dissipating up to 66.5% energy after the first impact (***Fig. 23***).

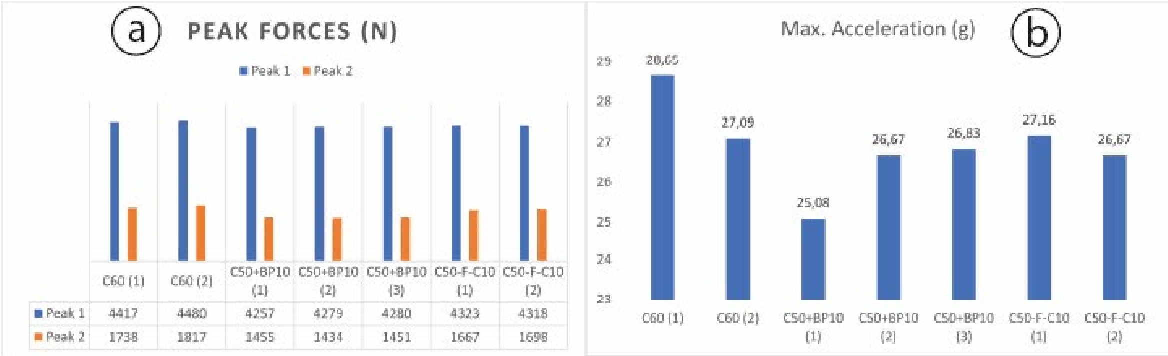


Fig. 22 - Comparison of various 60mm thick samples: a) Peak forces, b) Maximum acceleration

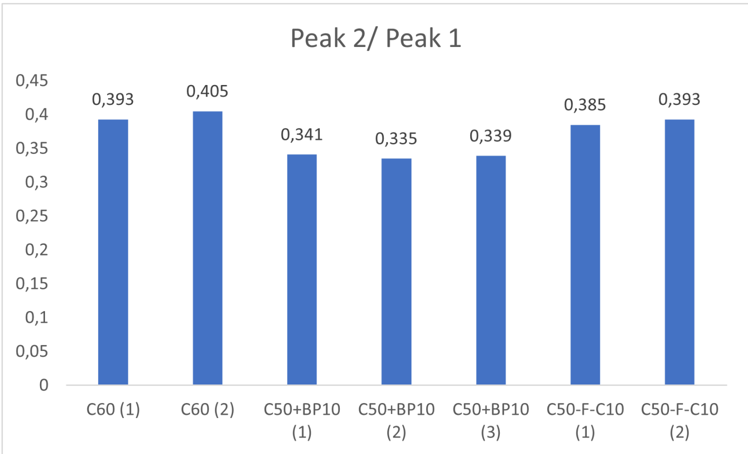


Fig. 23 - Relationship between the second and first peak forces of 60mm samples

The next round of samples to be evaluated is comprised of 60 mm cork blocks together with the PVC, impregnated fabric, and the 3.3 mm thick PU foam. Here, the PVC was the best performing material amongst the three in all of the three criterions: For the peak forces, although the fabric's maximum impact value is just slightly lower, the PVC has a substantially better performance when it comes to the second impact force, being it 25.5% lower than the best performing sample of "C60+TI" and 37.8% lower than the worst performing "C60+BP3.3" (***Fig. 24a***); its peak acceleration presents the best results and is 5.4% below the average and 13.4% below the "C60+BP3,3 (2)", which has the worst performance of all (***Fig. 24b***); and as for the dissipation of energy, it also leads the charts with 71.6% of energy dissipation in between impacts (***Fig. 25***).

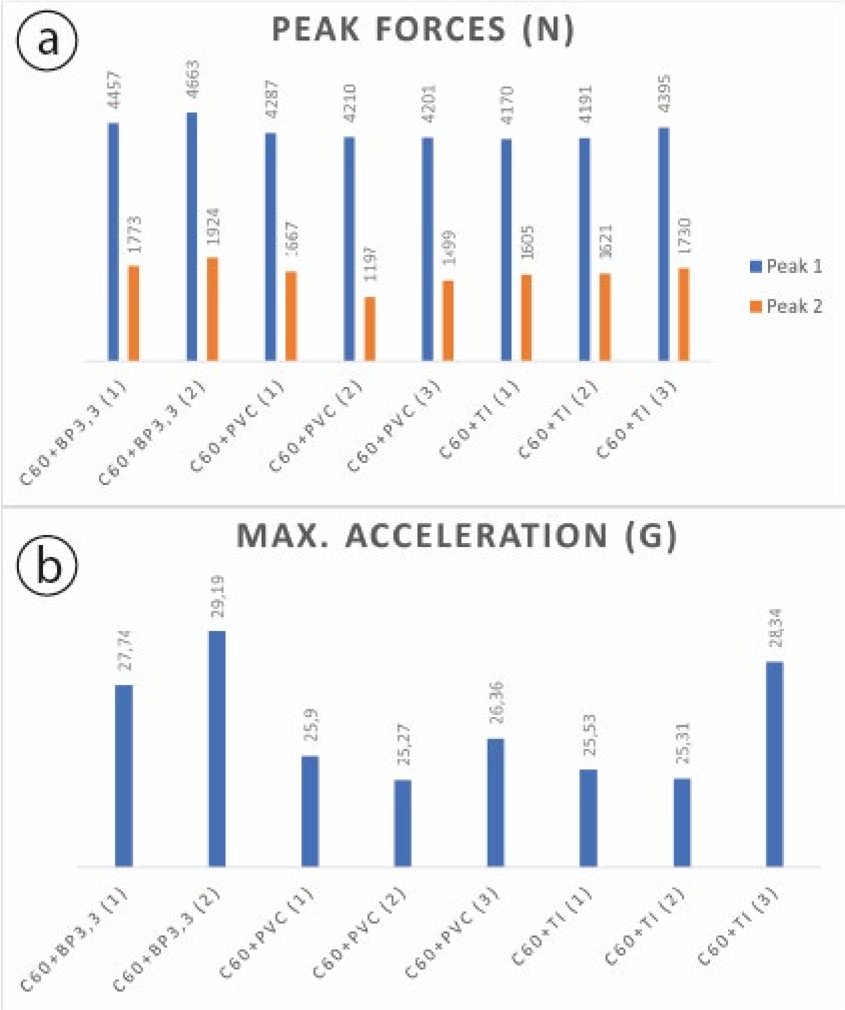


Fig. 24 - Samples' performance regarding a) peak forces and b) maximum acceleration

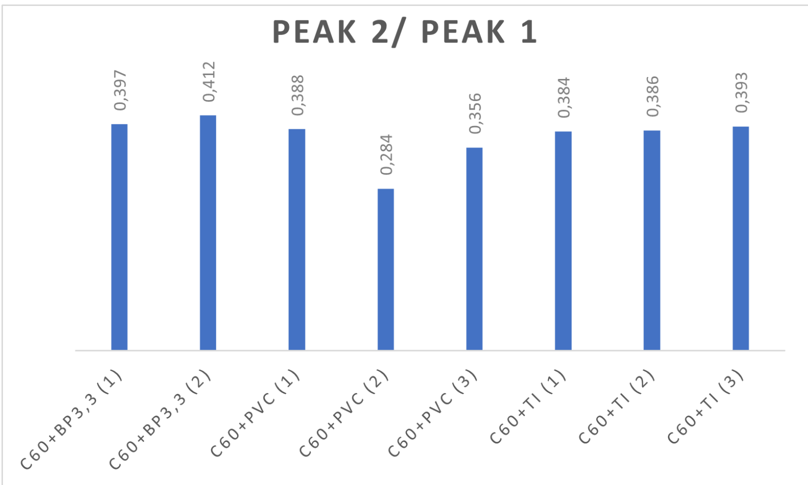


Fig. 25 - Samples' values for energy dissipation

Lastly, the samples combining cork, TPU and STF were tested. Like what had previously happened in the low-energy impact tests with the same materials configuration, the cork accompanied with TPU ("C30+TPU") had the highest value for the first impact, making it the worst performing combination in this regard. When the STF is added to it (C30-F-TPU), the peak force drops by up to 7.6% (***Fig. 26a***), proving again that the encapsulated fluid has a considerable influence in shock absorption. Because of its very high value concerning the first impact force followed by a relatively low one for the second impact, the "C30+TPU" appears as being the best sample for energy dissipation. However, this pole position does not necessarily contribute to an overall good performance of the sample when its first peak force is way above the average. The values for the "C30-F-TPU" samples are slightly higher, but still depict a very good performance with up to 72.6% of the energy being dissipated after the first impact (***Fig. 27***). Furthermore, the fluid shows one more time its potential to help reducing damage caused by excessive levels of acceleration. In this case, as shown by ***Fig. 26b***, the reduction is of 17.1% when compared to the "C30+TPU" sample and of 13.6% compared to the cork alone ("C30").

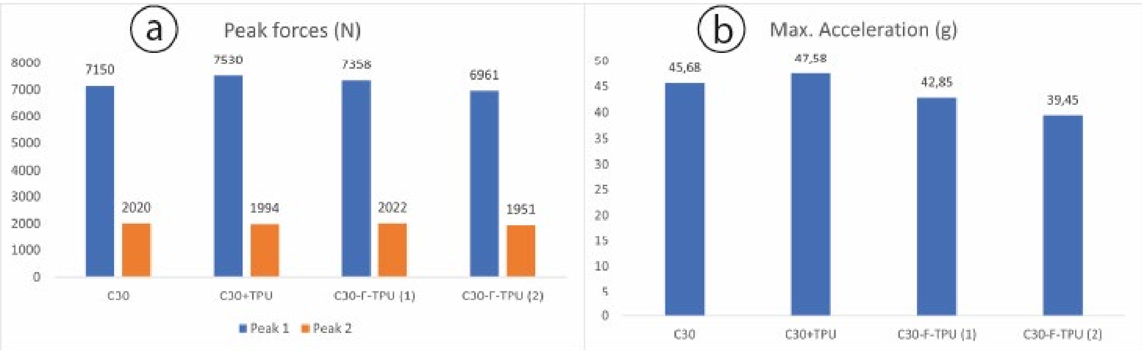


Fig. 26 - TPU and STF samples' performance regarding a) peak forces and b) maximum acceleration

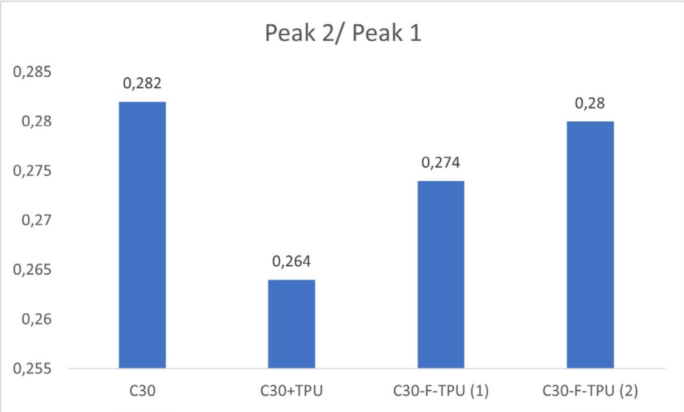


Fig. 27 - Sample's relationship between second and first peak of force

In common with the 20 J tests, the encapsulated fluid with TPU demonstrates good results concerning the reduction of peak forces and acceleration in the high-energy impacts. Overall, in absolute numbers, the "C30-F-TPU" has the best performance amongst the comparing samples – 17.1% decrease in acceleration and 72.6% of energy being dissipated. However, on the other hand, the STF used as an interlayer agent between two cork laminates ("C50-F-C10") did not have satisfactory results, performing way below its similar configuration ("C5-F-C5") that underwent the low-energy impact tests. Likewise, the impregnated fabric did not perform as well as it did when impacted at 20 J, proving to be inefficient for high-energy impacts. Surprisingly, the PVC had a good response to the 100 J impacts, with good levels of acceleration, peak forces and energy dissipation. Lastly, the 3.3 mm PU foam also did well and has the potential to mitigate high-energy impact forces.

One of the most important safety requirements for a helmet is to be able to reduce the acceleration of the protected object (in this case, the head) in the event of an impact. After conducting drop tests for both low- and high-energy impacts and considering the mentioned safety requirement, it becomes clear that the "cork-STF-TPU" configuration demonstrates the greatest potential to mitigate the impact energy coming from the impact and reduce the peak acceleration. Not only is the encapsulated STF a good configuration to be used in fields where energy absorption and reduction of damage is necessary, but also the agglomerated cork given that it is a material that undergoes high deformation when compressed, without suffering fracture or damage (Sergi et al., 2019). The cork's recovery capability in alliance with the STF's great ability to dissipate the impact energy and reduce acceleration has a good potential for the helmet industry.

4. Finite Element Analysis

4.1. Dynamic impact validation

In order to carry out virtual simulations with the purpose of testing the material's behavior in situations that would be otherwise costly or difficult in real life, it is necessary to first replicate the experimental tests in a FEA software like Abaqus. By replicating the exact same setup (sample material and size, and impactor's weight) and conditions (drop height, impact speed, boundary conditions, degrees of freedom), one can validate a material by tweaking the settings until the stress-strain curve of the virtual simulation matches the real one.

The sample chosen to be virtually validated was the "C60(1)" from the 100 J drop tests' series. It consisted of a cube of about 59,5 x 59 x 60 mm, which was modeled in Abaqus as a deformable object with the same dimensions and meshed with hexahedral elements with reduced integration (C3D8R). The impactor was modeled as an analytical rigid object and given a mass of 20kg applied to its reference point, and the impact velocity was set in the "predefined field" to be of 3.16m/s. To simulate the way the sample was positioned, a boundary condition was applied to the bottom face, restricting its displacement and rotation in the vertical axis. The stress-strain curve obtained from the experimental dynamic test (**Fig. 28**) was used as an input to define the material's properties, which was set as a "hyperfoam" with a strain energy of 3.

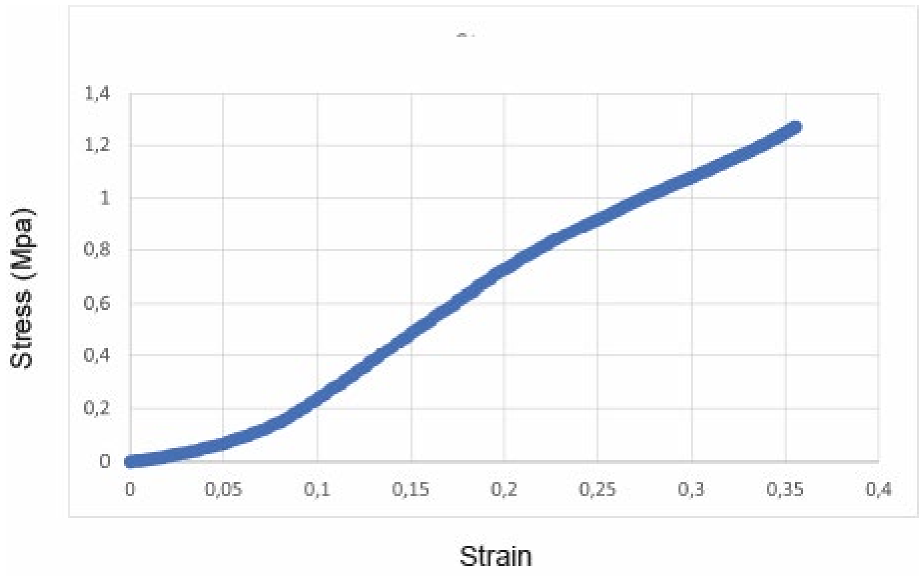


Fig. 28 - Stress-strain curve of the "C60" sample

However, the curve was not complete, i.e., the impact which the sample was subject to was not enough to define the typical three stages of such material during compression: the linear elastic regime, the plateau, and finally, the densification. Since the curve is missing the densification stage, the software was not able to properly determine the material constants for hyperfoam strain energy density function, therefore not reaching the desired results. Because of that there was the need to use the full quasi-static curve. However, as already described in the literature, cork is strain rate dependent between quasi-static and dynamic regimes. Therefore, the strain rate dependence needs to be taken into account. A method described by Gameiro et al (2005) was used, in which a stress-strain curve from a quasi-static compression test is multiplied by a factor of 3, resulting in an approximation of what would be the dynamic compression behavior of the material in question. This multiplication by a scale factor is possible because the agglomerated cork always presents the same shape of stress-strain curves. Quasi-static tests had also been performed to the same type of cork, and the resulting curve from the 1mm/min test was used and then multiplied by the aforementioned scale factor **(*Fig. 29*)**.

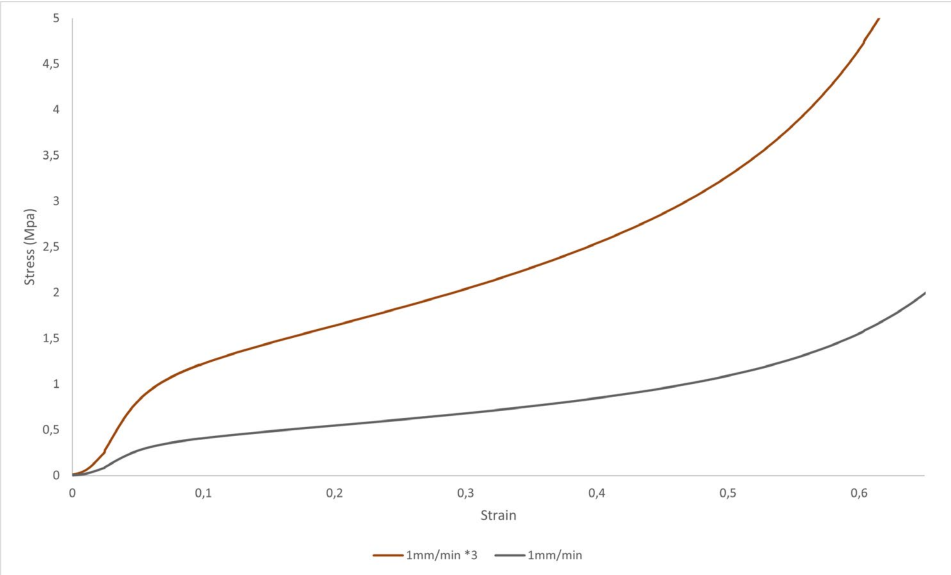


Fig. 29 - Stress-strain curve of the quasi-static compression test at 1mm/min and the same curve multiplied by 3.

Nevertheless, even though using the multiplied curve (by a factor of 3) as an input in Abaqus was giving better results than the dynamic one, it was still not matching. After many tries with different scale factors, it was found that simulation results of the 1mm/min quasi-static curve multiplied by a factor of 1.5 (***Fig. 30***) would match with the experimental dynamic curve (***Fig. 31***), thus validating the material. The difference at the very end of the curve does not affect the validation once the experimental curve's overall behavior has been successfully replicated.

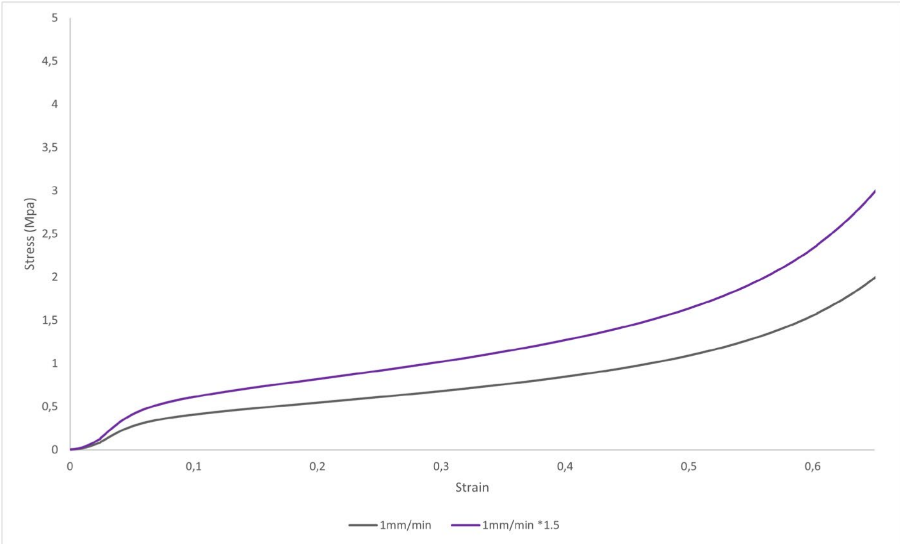


Fig. 30 - Stress-strain curve of the quasi-static compression test at 1mm/min and the same curve multiplied by 1.5

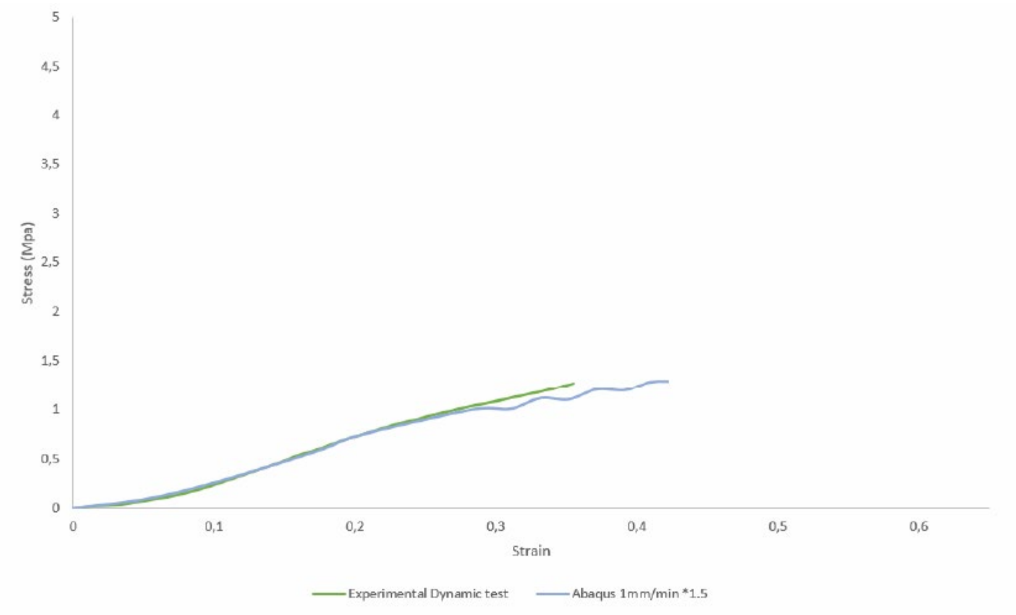


Fig. 31 - Simulation curve and experimental one compared

All the experimental campaign was done using a single type of agglomerate cork with a density of 180 kg/m^3. However, having more cork agglomerates of different densities would be useful to later assess how they would affect a helmet's performance regarding shock absorption. In order to do so, it would be necessary to validate other experimental dynamic impact tests involving additional types of cork agglomerates in Abaqus. Recurring to a master's thesis in which dynamic impact tests had been conducted on agglomerates of 120,160 and 200 kg/m^3 (Santos, 2016), it was possible to obtain the resulting stress-strain curves from the study (***Fig. 32***) and input their data into the software so that a virtual simulation could be done to validate them.

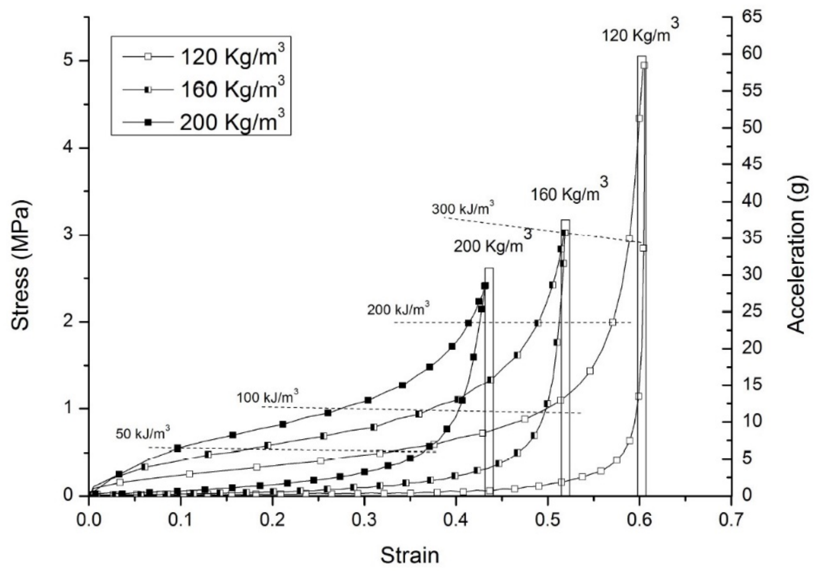


Fig. 32 - Strees-strain curves from dynamic impact tests of 120,160 and 200 kg/m^3 agglomerate cork (Santos, 2016)

The real conditions in which the experimental tests had been done were replicated in Abaqus: An impactor weighting 20 kg, impact velocity of 3.27 m/s and a sample with 50x50x50 mm. Just like the previous validation, the impactor was modeled as an analytical rigid object with a mass of 20 kg applied to its reference point, the impact velocity (now of 3.27 m/s) was defined as a "*predefined field*" and the mesh as C3D8R. Concerning boundary conditions and degrees of freedom, applies to this simulation the exact same definitions as before.

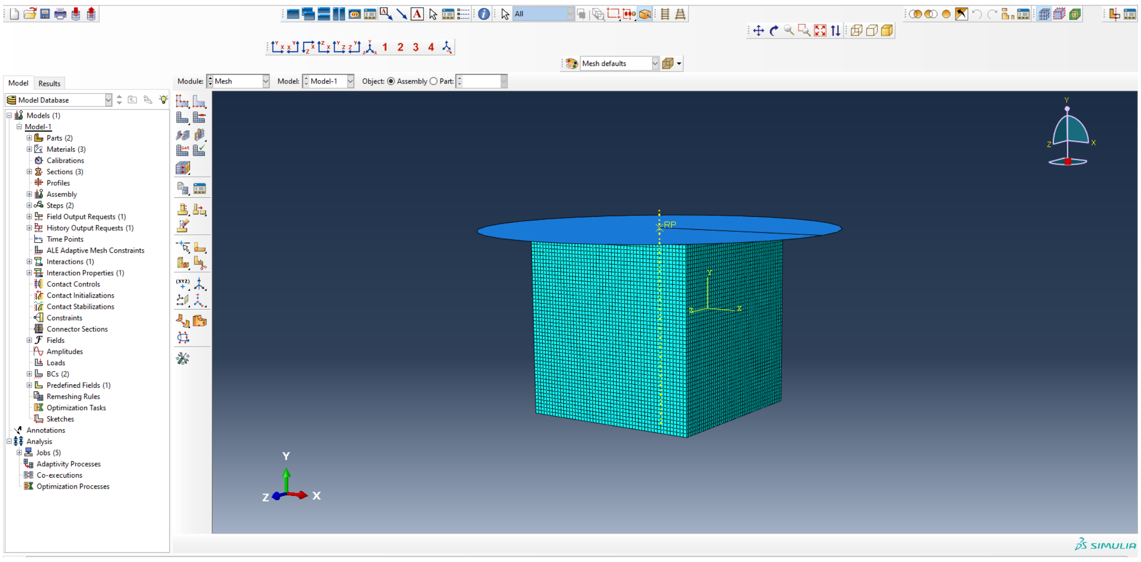


Fig. 33 - Overview of the simulation environment

Despite minor differences between the experimental and simulated curves, one can conclude that the materials' behavior was successfully replicated in the virtual scenario (***Fig. 34 to Fig*. 36**). With the validation of four different types of cork, it becomes possible to virtually test how these materials, applied to a helmet, can influence the peak acceleration of a headform under the conditions of a helmet safety standard, such as the EN 1078, CPSC 1203 or AS/NZS 2063.

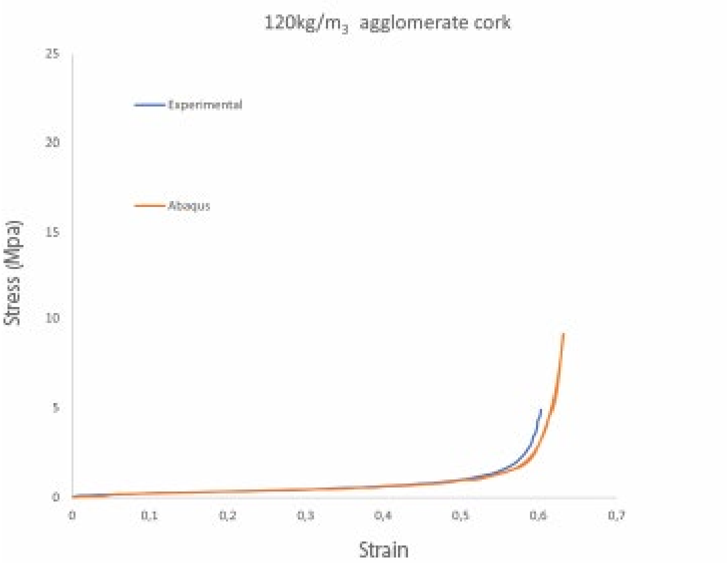


Fig. 34 - Curve from the virtual simulation compared to the experimental one from the 120 kg/m^3 cork agglomerate

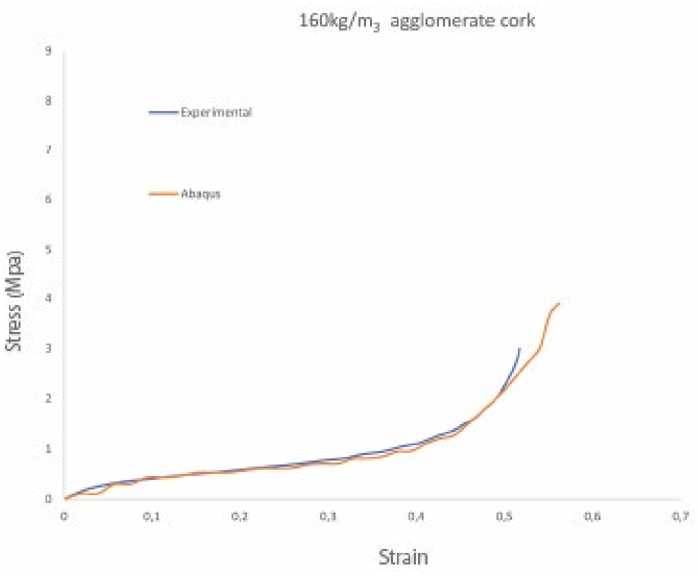


Fig. 35 - Curve from the virtual simulation compared to the experimental one from the 160 kg/m^3 cork agglomerate

Fig. 36 - Curve from the virtual simulation compared to the experimental one from the 200 kg/m³ cork agglomerate

4.2. Preliminary impact attenuation test simulation

For this step, a 3D model of a generic helmet was created from a model of a size J headform, the same one that is used by the EN 1078 standard, with the intention of testing the influence of the thickness in the shock absorption performance. Therefore, five models of the helmet were made, each with a different constant thickness – 10, 15, 20, 25 and 30 millimeters (***Fig. 37***). The simulations in Abaqus will test these models under the same conditions specified in the EN 1078, meaning that the headform weights 4.7 kg, the impact velocity is of 5.42 m/s against a flat anvil and the assembly (headform and helmet) falls free with all degrees of freedom.

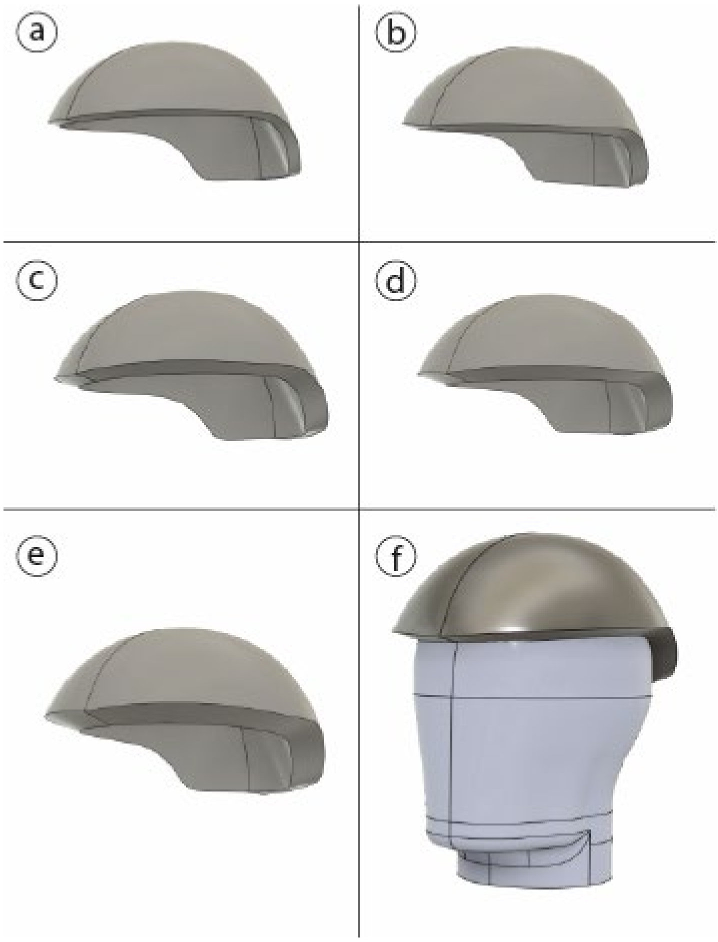


Fig. 37 - 3D models of the helmet with various thickness: a) 10mm; b) 15mm; c) 20mm; d) 25mm; e) 30mm; f) Helmet on the headform

The helmet models were saved as an .IGES file and imported into Abaqus as deformable objects. For the mesh, the object had to be partitioned in four to be able to use hexahedral elements with reduced integration (C3D8R), which was refined to 2.5 mm (***Fig. 38a***). The headform was imported as a discrete rigid object and it was meshed with triangular elements (R3D3) (***Fig. 38b***). Besides applying a mass of 4.7 kg to it, moments of inertia were also defined according to a study from Connor et al. (2019) that used the same size of headform (EN960-J) to assess how its mass and inertia influence the response to oblique impacts (***Table 9***). The corresponding data from the table was used and applied to a coordinate system created at the headform's center of gravity.

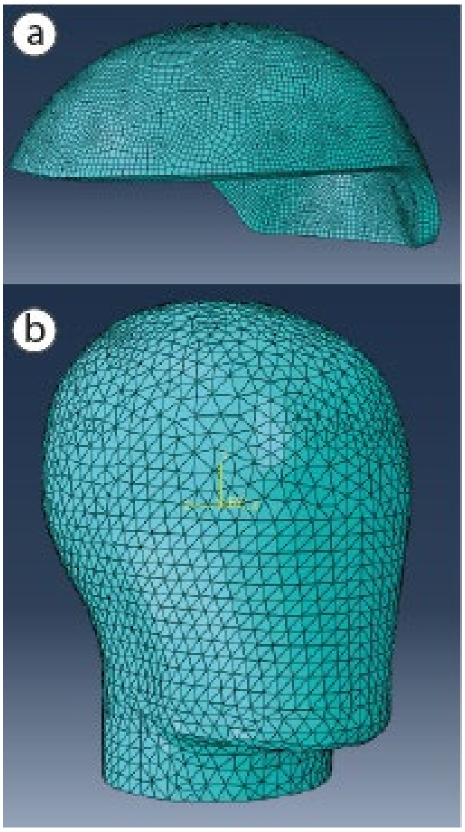


Fig. 38 - Meshes applied to a) helmet; b) headform

Table 9 - Headforms and their respective moments of inertia (Connor et al., 2019)

Headform	Mass (kg)	MOI (kg·cm²)		
		I_{xx}	I_{yy}	I_{zz}
EN960-*J*	4.7 (17)	224 (25)	307 (38)	206 (26)
EN960-*M*	5.6 (18)	318 (31)	399 (40)	277 (34)
HIII 50%	4.6 (5)	161 (−18)	221 (2)	179 (5)
PPLA-*M*	4.6 (0)	211 (−4)	241 (1)	192 (4)

The last object to compose the scene is the flat anvil, modeled in Abaqus as an analytical rigid body having zero degrees of freedom in every axis. The impact velocity of 5.42 m/s was set in the "*predefined field*", the interaction type is a "general contact" between all surfaces and the step field related to the impact has a duration of 0.025 seconds. A general overview of the simulation setup can be seen in ***Fig. 39***.

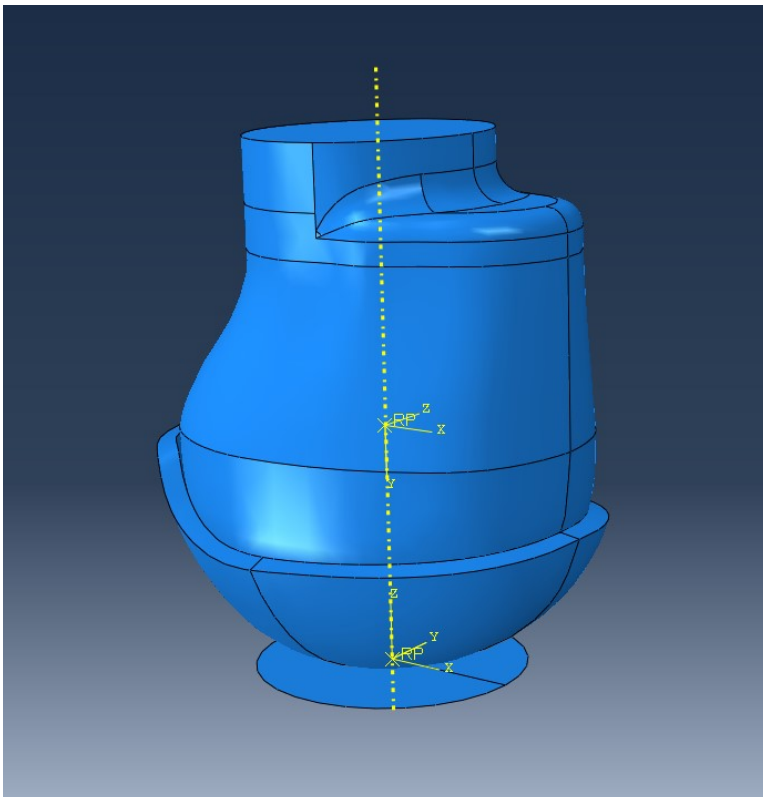


Fig. 39 - Overview of the simulation scene in Abaqus

These settings were replicated to every different model of the helmet and each of them underwent four simulations, corresponding to the types of cork previously validated – 120, 160, 180, 200 kg/m^3. The results (***Table 10***) indicate that the 30 mm helmet with a 180 kg/m^3 cork agglomerate is the best combination in terms of performance. In this configuration, the headform's acceleration reaches 230 g, which is already below to what the EN 1078 standard requires for a helmet's approval (250 g).

Table 10 - Results of the impact attenuation simulations in g

	120kg/m3	160kg/m3	180kg/m3	200kg/m3
10 mm	765,3	663,9	425,2	766,9
15 mm	645,5	539	338,6	446,1
20 mm	512,1	495,6	273,7	454,2
25 mm	412,4	370,5	243,7	334,9
30 mm	312,5	277,2	230	278,9

Looking at the table above, it is possible to notice that there is a significant difference between the 180 kg/m^3 cork and the other ones, especially for the 20, 25 and 30 mm thicknesses. This might be explained due to the fact that the cork samples used by Santos (2016) were produced by the author itself, unlike the 180kg/m^3 ones tested in this work that are industrially manufactured by Amorim Cork Composites. Therefore, factors such as resin type and amount, grain size, and the forming process conditions of the manually produced samples could have had a big influence in the final mechanical behavior of the material, leading to a lower performance regarding energy absorption. Such factors might explain the lack of consistency in some results, like the 15mm thickness performing better than the 20mm one for the 200 kg/m^3 density.

Considering the most promising result from the experimental campaign with high-energy impacts achieved by the shear thickening fluid encapsulated between the cork and the TPU, which demonstrated to reduce the acceleration by 13.6% when compared to the cork agglomerate alone, and applying it to the combination that performed better in the simulation – 30 mm thick 180 kg/m^3 cork agglomerate –, it is possible to assume that this solution decreases the headform's acceleration to a level below the 250 g threshold by a safe margin (202.8 g) and fully comply with the European standard. Moreover, the resulting value of 202.8 g peak acceleration is in accordance with two other studies that used FEA to simulate a drop impact test (at similar impact velocity –

5.44 m/s) with bicycle helmets, having the peak acceleration results ranged from 150 to 226 g (Mustafa et al., 2019; Mustafa et al., 2015). Even though the tests in the mentioned studies were performed on models with a different material (EPS foam of different densities), the conditions in which they were made are very similar (impact speed, headform size), allowing for a good comparison and to notice that a completely new combination of materials (TPU, cork agglomerate and STF) for this application has a comparable performance, emerging as a very promising solution.

5. Product development: objectives, constraints, and concept exploration

The topic that gives this thesis its name – “Head protection in electric micromobility” – is very current and becoming of great interest to many sectors of society. As elucidated by the first chapter of this manuscript, the rising numbers of accidents and serious injuries related to e-scooters are due to many different factors and, amongst them, there are design related issues. The perception of the shared micromobility user’s needs and the subsequent development of products that are adequate to them did not keep the pace of the category’s growth. Solutions that target this market and attempt to fill the gaps for improving convenience and safety are only starting to appear and, to this publication’s date, there are no data regarding their implementation and performance. However, the existing problems go beyond the product’s usability and suitability. Sustainability, which encompasses a product’s material, how it has been sourced, the manufacturing processes involved and its introduction in a circular economy, is a key factor that needs to be tackled within the design phase of a product’s development since it is estimated that about 80% of all product-related environmental impacts are determined during this phase (EU Science Hub, 2021).

In this chapter and the following, all the processes of designing the final solution will be discussed: from the identification of the users and their needs, the design intentions, choice of materials, circular economy, concepts development, study of the product's life cycle assessment (LCA), and design for assembly and manufacturing.

5.1. Identifying the users and their needs

Research is a crucial part in a product's development process because it allows the designer to understand the people and the context to which they are designing for. Products are used in the real world and their use encompasses environmental, social and economic factors, therefore anticipating the broad spectrum of use is important to help ensure a good experience. Empathy towards the user of a final product or service is an important foundation that lets the designers channel their concerns and needs while suppressing their own biases (King & Chang, 2016).

As referred to in this manuscript's state of the art, the average user of e-scooter sharing systems can be described as being male, mean age around 29 years old, upper-to-middle income, with high levels of educational attainment. Their motivation to use e-scooters is mainly to replace short walking trips on the way to work or university. Besides the use by workers and students, the use for leisure by tourists in a foreign city also represents a large portion of this shared vehicles' audiences. Despite the very different types of users, which may lead to some behavioral differences due to the distinct natures of use, they all share one important aspect: they are spontaneous riders that do not use the e-scooters on a regular daily basis. According to 6t-bureau de recherche (2019), only 7% of the users rent out a free-floating e-scooter every day or almost every day in France, numbers that are similar to the results from the Austrian study conducted by Laa & Leth (2020), which concluded that only 5% of the users would use the vehicle several times a week. Moreover, still according to the French study, 44% of users rented out an e-scooter only to take a one-way trip, making the way back (or vice versa) with public transportation (57%) or by walking (37%). This, besides suggesting a strong compatibility between the e-scooters and these two other modes, reinforces the spontaneous nature of this kind of shared transportation.

Fig. 40 - Representation of the users of e-scooters rental services

From the observation of rented e-scooters users in the cities and searches on the web for news and articles (related to the rental e-scooters theme) that contain pictures, one can withdraw some key conclusions. First, the mean age of the users portrayed in the literature matches what can be seen in general through observation and on imagery from media coverage (***Fig. 40*** is part of the author's picture database with a collection of images from many different sources related to the subject). Second, the very low rate of helmet use described in many studies (see section ***2.5.1*** of this manuscript) is also noticeable in observations and pictures. In the latter, very few of the photographed users wear a helmet – from 108 pictures of the author's database, only two of them contain a person wearing one (1.8%). Lastly, given the main nature of the trips (work and study) and the public's mean age, it is safe to say that many of the users have some sort of bag with them, whether it is a backpack, a briefcase, a bag, a large or small purse, in which they can carry their personal items to and from their destination.

In short, young adults are increasingly using shared e-scooters to commute mainly to work or study. However, for many reasons (availability, price and other momentaneous personal preferences), such mode of transportation is used more spontaneously, meaning that the great majority of users do not use them on a daily basis nor on an orderly way, they use it when they see fit. This irregular use of the vehicle in addition to the fact that there are no available helmets with the e-scooters and, due to the spontaneity of the trips, carrying its own helmet (which occupies a reasonable space that most users do not have available in their bags) is not convenient, make up the main identified reasons for the low helmet usage that culminates in the growing number of injuries from e-scooter related accidents.

5.2. The design's perspective on the identified main issue

The state-of-the-art section of this manuscript discusses in depth what are all the contributing factors (unclear legislations, law enforcement, among others) for the low use of helmet amongst shared e-scooter users and the consequent rise in numbers of serious head injuries and hospitalizations as a result of accidents involving these vehicles. However, in this section, the discussion will be focused on a factor that, unlike legislation and law enforcement, can be tackled by design strategies: the inconvenience of a spontaneous rider having to carry its own helmet.

Helmets can be inconvenient in a couple different ways for the spontaneous riders: having to look for one and to dispose of financial resources in order to have it;

and the need of carrying it around and storing when not in use, which demands either opportunity costs, access to secure storage or plenty of space in the bag (considering the size of most helmets), is perhaps the biggest inconvenience. The helmets available have not been designed for this context of use, which main requirements are portability and convenience. Very few foldable solutions exist in the market, and they can only reduce their volume in up to 33%. Even though this reduction may already help fitting a helmet inside a backpack or bag, where most conventional helmets cannot properly fit, it still contains another problem that is directly linked to the financial inconvenience: its price. Foldable helmets, in general, cost more than €100, making it a big barrier for the shared e-scooters user. Such high prices make it also unfeasible for sharing services to implement any type of solution involving these more convenient kinds of helmet, such as distribution campaigns or attaching them to their vehicles.

However, integrated solutions are just starting to appear (see ***section 2.8*** of this document) and the one coming from the German e-scooter rental company "TIER" currently stands out for being the first integrated solution amongst e-scooter companies and the only one with a foldable helmet. The company announced the feature in June 2020 and there is no available data regarding its current state of implementation and use. The date of announcement and the fact that there is only one more identified solution of this kind for e-scooter sharing demonstrates that the issue is only starting to be addressed and there is room for more alternatives, improvements, and innovation. For instance, a more versatile solution can be achieved, one that is not exclusively integrated to the vehicle but that could also be owned by the customer. Moreover, the sustainability must be tackled and that has not been the case for what has been developed so far. Solutions are strongly focused and what has been the standard in the helmet industry for decades: the use of plastic and synthetic foam. The world urges for a change in how products are developed throughout all industries, and sustainability must be present since the early stages of the design process, with a special attention to material choices, manufacturing processes and the introduction of the final product into a circular economy.

5.3. The design intentions

Considering all the aspects of the problem, it has been identified the need for a solution that is both portable and convenient for the user while also having the possibility of being integrated into the sharing e-scooter business model, whether by incorporation in the vehicle itself and/or by financially viable ways of its distribution or rental.

To fulfill the requirements of portability and convenience, while also filling the existing gap and driving innovation in the helmet industry, the functional aspect of the proposed solution aims to total foldability. The objective is for the helmet to be able to flatten completely, reducing its volume to levels way above what current foldable solutions in the market can offer, therefore making it easy for anyone to fit it into backpacks, bags or even suitcases.

Another important aspect of the aimed solution is the sustainability. As previously mentioned, the existing helmets are mainly made of plastics and synthetic foams, which are not good for the environment. Especially when bearing in mind the fact that these protection devices cannot offer the same level of protection after the first impact due to the more plastic behavior of the synthetic foams, like EPS, which suffer permanent deformations and no longer return to its original structure. This means that these helmets have a short life span and will be disposed after the first damage, resulting in more plastic and foam in the trash and later filling up the landfills. This process and culture of quick disposal belongs to the traditional linear economy that urgently needs to be changed and transformed into a circular economy instead. To change this and enable the helmet to be fully circular, the synthetic foam will be replaced by white cork agglomerate. Besides its great performance in energy absorption when compared to the traditional foams (F. A.O. Fernandes et al., 2015; Sergi et al., 2019; Varela et al., 2020), it can also be grinded when it reaches the end of its product life cycle and new agglomerate panels can be made from it, allowing the continuity of the production cycle. This way, what was previously considered to be waste can be transformed into a new batch of products. Not to mention that cork is a natural cellular material, unlike the synthetic ones that are petrol-based.

The final solution aims to bring innovation through the design, not only by challenging how a helmet is used and perceived as an object but also by using mostly natural materials, facilitating its introduction into a circular economy, which would be a revolutionary achievement for the helmet industry and very appropriate for the shared micromobility. The four pillars in which the product development is based are, as seen in ***Fig. 41***, the following: viability, desirability, sustainability, and feasibility.

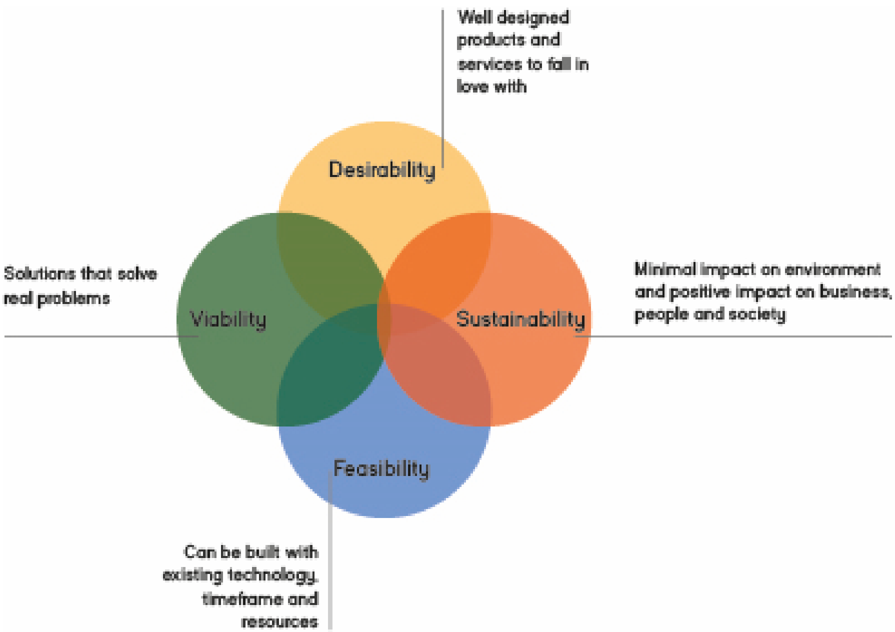


Fig. 41 - The four pillars in which the solution is based

5.4. The material choice: Why Cork?

From early in the design process, it was defined that cork would be a material constraint for the product development. Through the research phase, the material was found to have a great potential to be used in an application that requires shock absorption, like helmets and protective equipment. Not only can they perform well mechanically, but also environmentally, given the fact that the material is in the core of the sustainable development concept. Besides its great attributes in the field of sustainability and mechanical properties concerning impact resistance, cork has never been commercially explored for this type of application, what creates an enormous potential for innovation in the field.

5.4.1. Cork's properties and importance

Cork is a 100% natural material, reusable, recyclable and with many great properties such as being lightweight, hypoallergenic, impermeable, a good thermal and acoustic insulator, among many others, all of which makes it one of the world's most versatile materials. The cork comes from the bark of the cork oak tree, the only tree whose bark regenerates, acquiring a smoother texture after each harvest. There is over 2.2 million hectares of cork and about one third is situated in Portugal, country which is responsible for 55% of the world's cork production (Amorim Cork Composites, 2021).

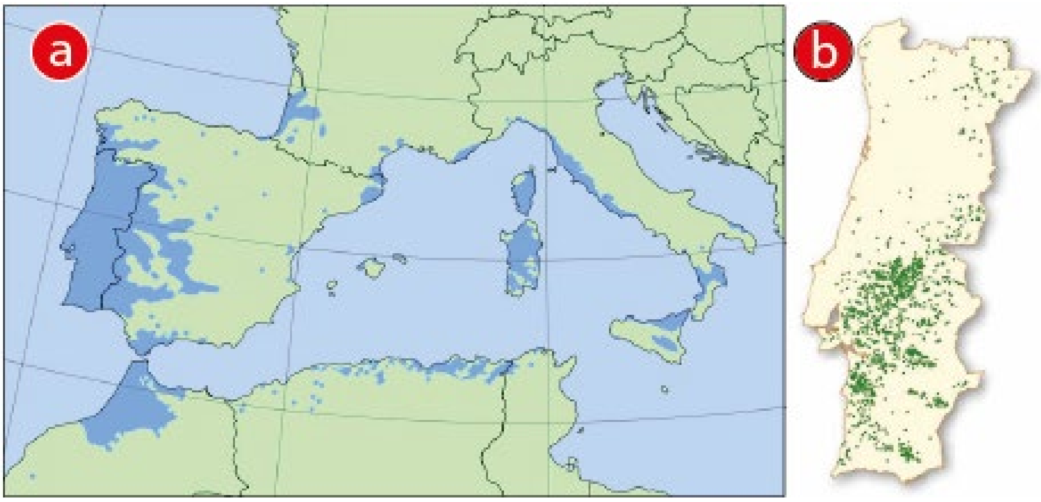


Fig. 42 - a) Cork oak forest distribution in the Mediterranean region (EUFORGEN, 2009)*; b) Cork oak forest distribution in Portugal* (National Geographic Portugal, 2017)

An interesting aspect is that the harvest of cork does not make it an endangered natural resource, on the contrary, because it is a controlled process and does not require the trees to be felled, it contributes to their regeneration. They are harvested every nine years and over the course of its lifetime (around 200 years), it may be stripped around 17 times, because it takes the cork oak 25 years before it can be first stripped and 43 years to have the high standard of quality required for producing cork stoppers. According to Gil (2013), after the bark is extracted, the tree regenerates the bark for its own protection (it is a natural protection against fire), promoting more CO_2 fixation as a direct consequence. Studies estimate a sequestration of up to 73 tons of CO_2 for each ton of cork produced, therefore helping to reduce the global warming potential (Amorim Cork Composites, 2021).

Besides the sequestration of CO_2, cork also possesses two other characteristics that places it into the heart of a sustainable development: its close relation to the maintenance of biodiversity and its economic importance (Gil, 2014). The former consists of the fact that the cork oak forests are home for 135 plant species and more than 200 animal species (natural habitat for 60% of Portugal's mammals). This puts the cork forest as one of the 35 most important ecosystems in the world for preserving biodiversity, alongside the Amazon rainforest and the African Savanna (Amorim Cork Composites, 2021). The latter is due to the existence of many jobs directly or indirectly dependent on the cork. It is estimated that, in Portugal alone, there is approximately ten thousand jobs in factories, 6500 jobs in harvesting and more thousands of indirect jobs in tourism, catering and many others. And according to the World Wide Fund for Nature (WWF), over one hundred thousand people in southern Europe and north Africa depend on these forests. The cork industry can be considered to be the driving force for sustainable development in the region, helping to create and maintain thousands of jobs while preserving the natural ecosystem and contributing for reducing greenhouse gas emissions.

Cork also plays a very important role concerning Portuguese traditions and the construction of a national identity. The country is certainly very well-known for its production of wine and good food, however, outside culinary, there are two other things, in the realm of materials, that represent Portugal like no other: ceramics and cork. Both are part of the country's history, even though the former dates back to longer ago. However, there are indications that cork was used in the caravels of the Portuguese navigators, in the Discoveries era. Moreover, it was used by the monks in their monasteries to make their common areas, lined with cork, more comfortable. Examples of this can be seen in the 'Convento dos Capuchos', in Sintra, and in the 'Convento da Serra da Arrábida' (VisitPortugal, 2013). The importance of the cork oak is such that in 2011 it was declared by the Portuguese Parliament to be the country's national tree and has been protected by law since the 13th century.

5.4.2. Cork agglomerate

The extraction of the tree's bark is the first step in the process of making cork. There are several other following processes that are necessary until the cork is ready to be transformed into products. Most of the processed cork, still in its natural state, is used to produce stoppers. The scraps, parings, and other stopper production waste are grinded and mainly used as raw material for the manufacture of agglomerates. There are two main categories of cork agglomerates: the black/expanded cork agglomerates and the white agglomerates (***Fig. 43***).

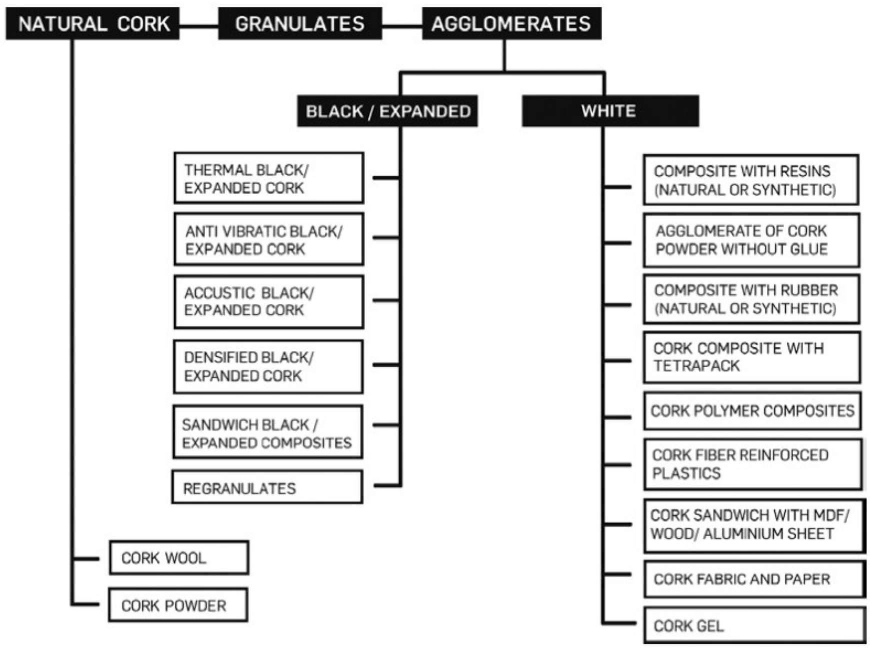


Fig. 43 - Schematic of existing cork materials (Mestre & Gil, 2011)

The black/expanded cork agglomerates are a natural product made through a process of agglutinating granules of crude virgin cork. This process is carried out by an autoclave that, while subjecting the granules to high levels of heat and pressure, also works as mold, giving form to boards of different thicknesses. A natural resin (suberin) found in the tree's bark is used in the agglutination process and, because of its high amounts, the resulting color of the agglomerate is much darker (Kaczy´nski et al., 2019).

The fact that no synthetic binders are used in the process makes these boards a very sustainable choice of material. However, when it comes to mechanical properties, specially under impacts, it was found that the expanded cork agglomerate can be structurally damaged under moderate rate of impact energy, making it less stable than the white cork agglomerates and, therefore, less suitable as a multi-impact energy absorber (Ptak et al., 2017). On the other hand, according to the same study, the fact that it tends to crush under a lower load than the white agglomerated cork might be interesting in terms of head injury mitigation.

The white cork agglomerates are made from waste products of the stoppers production and also recycled stoppers. The recycling of stoppers is a great way to add value to the material by enabling the creation of new products – with sometimes enhanced properties, such as isotropy, because of the agglutination process – instead of being wasted (***Fig. 44***). This composite, that commonly involves synthetic resins – mostly polyurethane – maintains all the properties of the cork and acquire new ones by controlling the granulometry and density. White agglomerates come in many sizes and thicknesses, can undergo various transforming processes and be used in a vast range of applications, from home furniture to civil construction and the aerospace industry (Mestre & Gil, 2011). Despite the use of synthetic binders for producing this type of agglomerate, according to Sierra-Pérez et al (2016) in a study about the white cork agglomerate's life cycle assessment, they only account for 6.8% of its global warming potential (GWP) and, considering all the steps involved in manufacturing one functional unit of the material, the white cork agglomerate has a negative carbon footprint of 2.86 kg CO_2 eq (if biogenic carbon content is considered). Regarding the white agglomerate's performance when subject to compressive loads, it has the advantage of experiencing high levels of deformation without undergoing fracture or damage (unlike the black/expanded cork). Because of its recovery capabilities, it is a material of great interest in all applications where multi-impact energy absorption is required (Sergi et al., 2019).

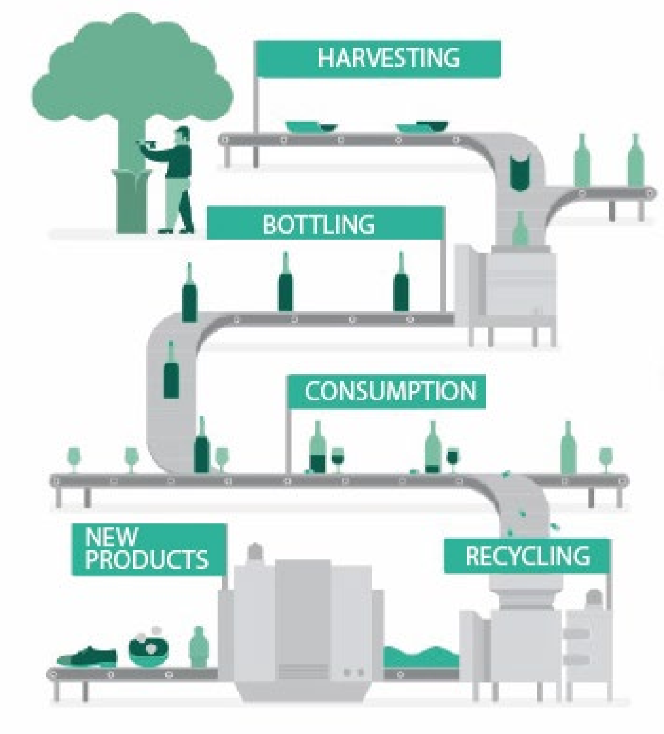


Fig. 44 - Recycling of wine stoppers

5.5. Concept exploration

This stage of the process is very exploratory and consists in generating ideas that can possibly become design solutions. All the data and information that has been gathered throughout the process will serve as guidelines for thinking about solutions and expressing it graphically. This is a phase of diversion, where multiple different ideas will be explored in the attempt of finding the best suitable solution for the identified problem. After the refinement of ideas, the most prominent concepts are chosen to be carried on and have their feasibility and suitability tested with physical mock-ups and, after several iterations, conclusions will be taken which will lead to the development of the final concept and solution.

5.5.1. Morphological analysis of the helmets in the market

Many of the current helmets bet on an aerodynamic and futuristic look (***Fig. 45***). This trend is set for several reasons, being the materials used and the technology available one of them. The conformation of plastics through thermoforming and other technologies allows for more complex and bold designs. The aesthetics is also driven by performance reasons, since the holes spread all over the helmet are important for ventilation, especially for professional bikers. However, the trend has also spread to casual helmets, therefore becoming the norm nowadays. It applies even for the foldable/collapsible helmets, as it possible to notice in ***Fig. 46***.

Fig. 45 - Aesthetics of the current helmets in the market

Fig. 46 - Aesthetics of foldable/collapsible helmets

Few are the examples of casual helmets that stay away from this design trend and try to focus more on casualty and practicality instead. One example that had already been mentioned in the *section 2.7* of this document, the EcoHelmet™ (***Fig. 47*** on the right), a helmet made completely out of cardboard, failed to comply with safety standards and has never officially been launched in the market. Another example is the Park & Diamond's cap look-alike helmet (***Fig. 47*** on the left), which was crowdfunded in 2020. Nevertheless, up to this manuscript's publication date, it has not yet reached the market.

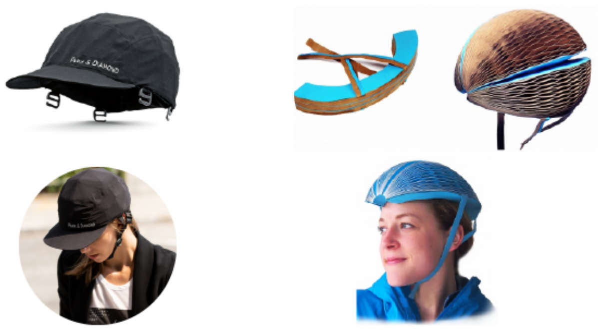


Fig. 47 - Park & Diamond's helmet on the left; EcoHelmet™ on the right

The intended solution should step away from the modern and futuristic looking models and also innovate in the aesthetics, by focusing in providing a convenient and practical helmet with the ability to fold flat. The function and materials defined to be implemented are going to directly influence the solution's aesthetics. Highlighting the use of cork, an innovative material for the application, is also a design intention. Thus, given all the different ways in which the solution aims to innovate, the intention is to bring something unique to the market and disrupt the predefined idea dictated by the current available models of what a helmet should be and look like.

5.5.2. The anatomy of a helmet

The helmets that can be seen in figures 45 and 46 reflect the absolute majority of what can found in the market within the category in terms of aesthetics, materials, and anatomy. As briefly explained in the section 2.7 of this manuscript, the helmets are usually made of three layers: the outermost most one, the hard shell, is made of materials (PC, ABS, HDPE) capable of absorbing plenty of energy during plastic deformation, thus spreading the impact force along a wider area; the middle one, the protective padding, is made of materials that undergo large levels of deformation when subject to compression forces (usually EPS); and lastly, the comfort padding, made of softer materials in order to provide comfort when in contact with the wearer's head. ***Fig. 48*** illustrates the anatomy of a typical bicycle helmet.

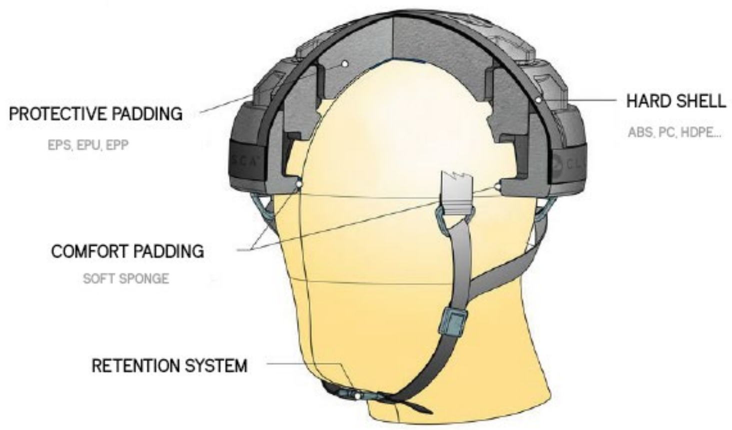


Fig. 48 - Helmet's typical anatomy. Adapted from (CLOSCA, 2013)

Such configuration is very effective in terms of protection and has been used for this application for decades. However, with the evolution of materials and technology, the tendency is for having new ways of achieving the same level of protection. A great example is the surge of shear thickening fluids and materials with viscoelastic properties, such as cork, that are able to ensure protection for multiple impacts. Not only there is a potential for performance improvement, but also to bring change to the device's aesthetics, that are very much based on the three layers configuration.

5.5.3. Helmet's area of protection

An important aspect to consider in the helmet's design is its area of protection. This area is defined by the safety standards through which the devices must undergo and comply in order to successfully reach the market. In Europe the standard is the EN 1078 and is used as the reference for this work. The test area is determined based on the dimensions of each headform established in the EN 960 standard, therefore the precise measures vary according to the head and helmet size. The guidelines to determine exactly what the test area is, is specified in the section 5.4.1 of the norm (European Standard EN 1078, 2008). However, it is possible to have an idea of the test area by the visual representation in ***Fig. 49***.

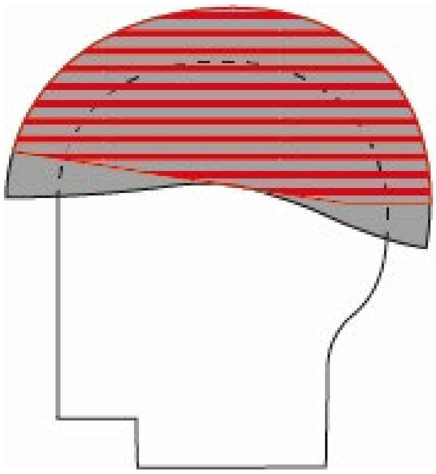


Fig. 49 - Visual representation of the approximate helmet's test area (in red), according to the EN 1078 standard

The highlighted area in red is the one subject to the impact tests, therefore the most important part to consider when designing the helmet. After all, the solution should not just meet the users' needs of practicality and convenience, but also their need of protection during the spontaneous rides, what makes it crucial for the final design to comply with the current standards.

5.5.4. Ideation

Many ideas for concepts have been generated at this stage, creating the opportunity to later explore their feasibility through mock-ups. The following ideas are an answer to all the tests that have been made so far that led to the conclusion that using cork with encapsulated STF would provide the helmet with the best performance in terms of shock absorption, making it comply with the current safety standards. The form exploration was based in trying to find solutions to conforming the cork to the head, mainly through more simple and conventional transforming operations (CNC milling and machining) that are adequate do the material in question, i.e., cork agglomerate boards. The ideas also explore the use of other materials, such as elastic bands and fabrics, in an attempt to help make the cork conform and fit to the user's head. The concept ideas can be seen next in the ***figures 50 to 55***.

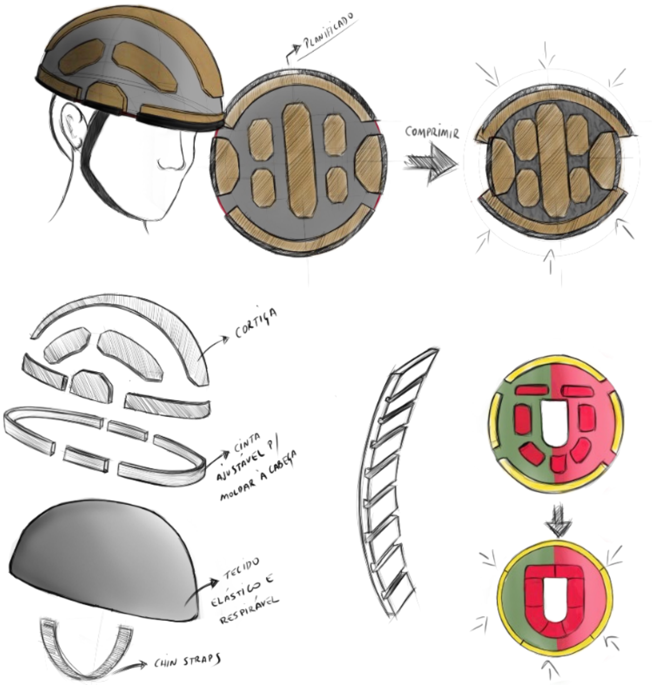


Fig. 50 - Concept 1

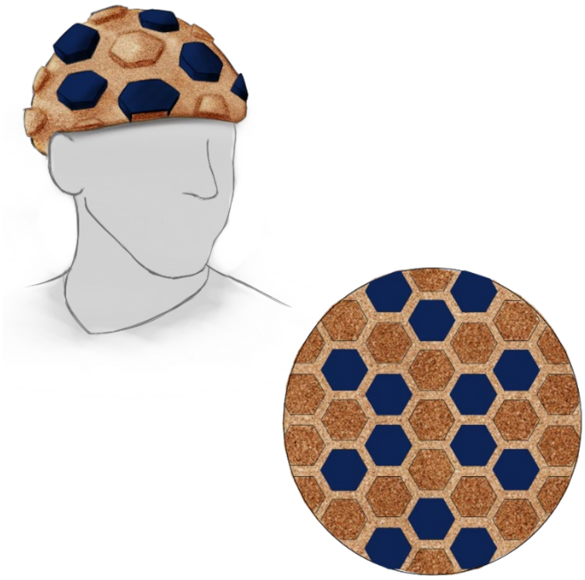


Fig. 51 - Concept 2

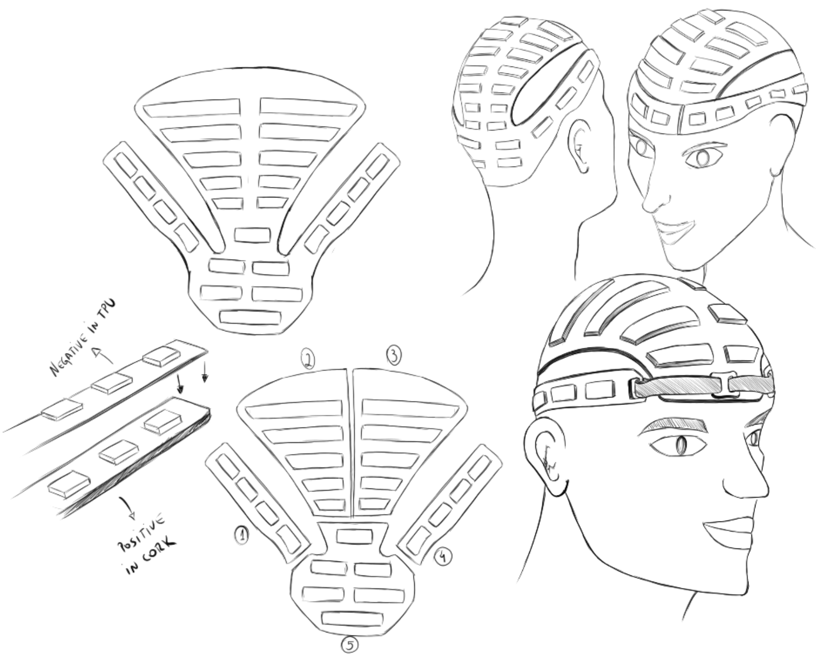


Fig. 52 - Concept 3

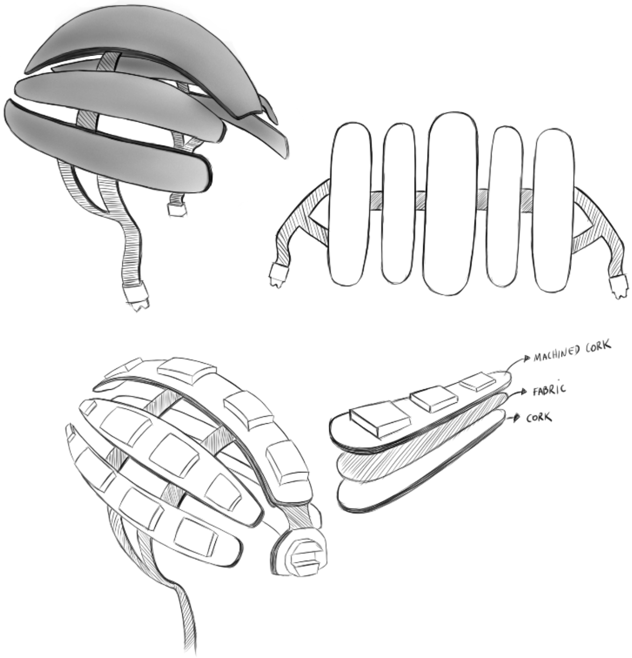


Fig. 53 - Concept 4

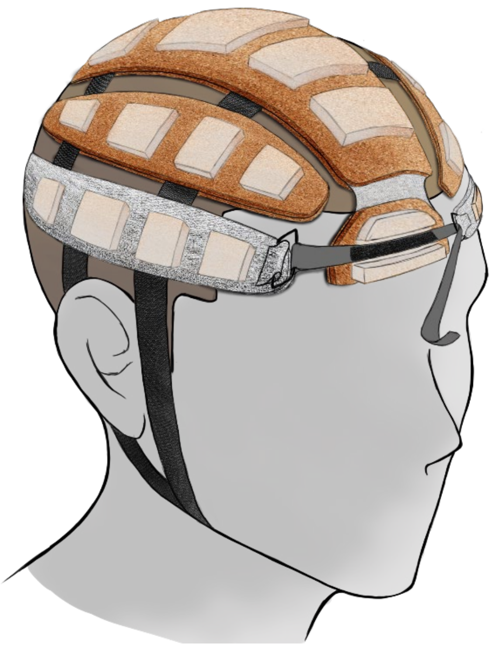


Fig. 54 - Concept 5

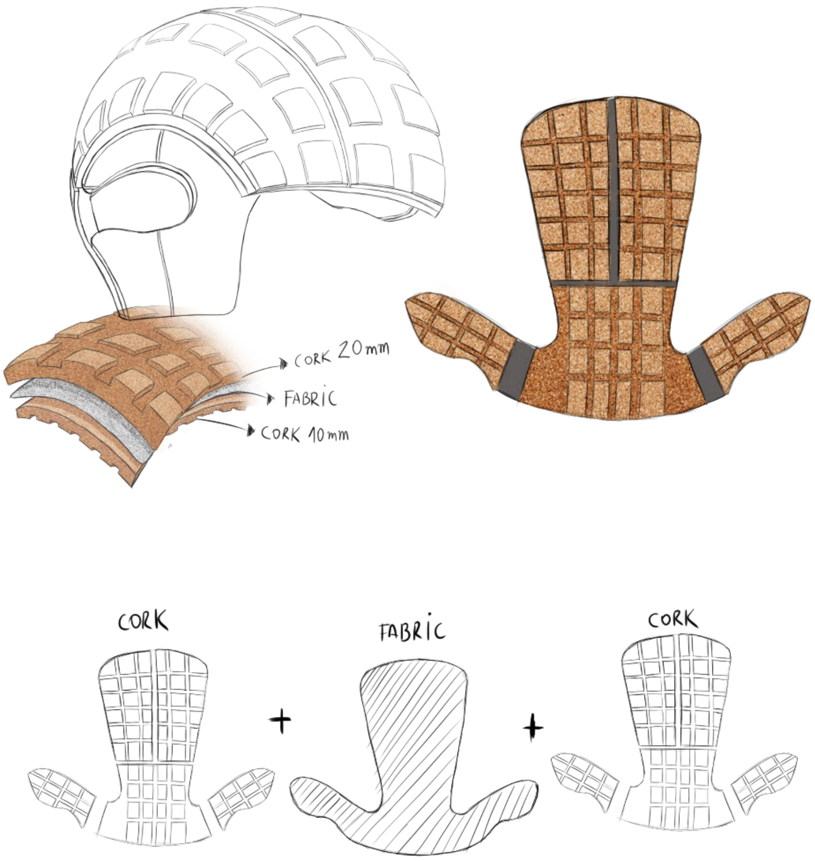


Fig. 55 - Concept 6

5.5.5. Iterations and validation of concepts

The main concern as well as the main challenge in the development of the desired solution is to conform a plain cork agglomerate board to a person's head through subtractive manufacturing. Therefore, the represented concepts focus more on that matter than on other elements of the helmet. However, since the challenge is intrinsically related to the material's behavior when subject to a specific transformation technique (and there are no other similar work and case studies to take conclusions from), the ideas are not enough, and the concepts must be subject to physical testing to check whether the solution is feasible and adequate.

For allowing to evaluate how the material would behave in reality, the iterations with physical mock-ups are a very important part of this project's development. Several experiences have been made, allowing for conclusions to be taken from each one of them. Some led to the finding of new possible solutions and were of extreme importance for building the path towards the final design proposal.

Fig. 56 - Iterations regarding concept 2

Fig. 57 - Iterations regarding concept 4

Fig. 58 - Iterations regarding concept 6

One of these findings was related to the use of fabric in between two pieces of cork (***Fig. 59***). The simulations run in Abaqus (see ***section 4.2***) revealed that a thickness of 25 mm should be enough to reduce the headform's peak acceleration to levels that would comply with the standards. However, with this thickness the peak acceleration would be just slightly below the norm's threshold and since the acceleration can vary according to the region of the impact because of the moments of inertia, it would be safer use a thickness of 30 mm. On the other hand, the thicker the board of cork agglomerate, the more difficult it is to make it more flexible and conform to a head's shape. However, if instead of one entire board of 30 mm, two boards – one of 10 mm and another of 20 mm – were used and glued to a fabric (in between the pieces of cork), the flexibility would be improved exponentially. Moreover, with the fabric in between, the cork does not need to be used in one piece, allowing for several pieces to be glued to the fabric to form a desired shape (***Fig. 60***).

Fig. 59 - Several pieces of cork glued to a piece of fabric and how it affects the bending of the entire system

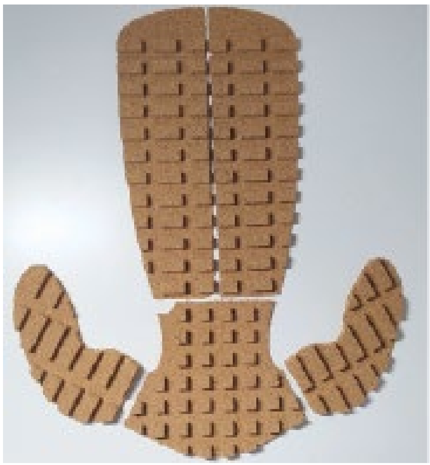


Fig. 60 - Separate pieces of cork before being glued to a piece of fabric with the shape of the whole

Another important finding related to the cork's flexibility concerns the depth of the machining operation. There seems to be an optimal depth of cut that ensures a very good balance between flexibility and resistance. The depth depends on the board's thickness, but it should always leave 2.5 mm of material. For instance, in a 10 mm thick board, a 7.5 mm deep cutting operation creates a very flexible piece of cork that does not break nor gets damaged when bending (***Fig. 61***). The same is valid for a 20 mm thick board, where a 17.5 mm deep cut will provide good results in terms of flexibility. However, it is important to note that the thicker the material, the less flexible it will be after the operation.

Fig. 61 - Flexibility of a 10 mm piece of cork machined 7.5 mm deep

All these iterations were important to understand how to work with the material in order to achieve the desired level of conformity. After learning how to transform the cork and what is feasible, other important aspects of the helmet could be focused on, such as the ease of wearing and adjusting it. From there, the final iterations that ultimately resulted in the final solution started to be made (***Fig. 62***, ***Fig*. 63 *and Fig. 64***). The last conclusions and findings pointed out the need for adjustments. The final concept will be introduced in the next section.

Fig. 62 - Iterations for the final solution

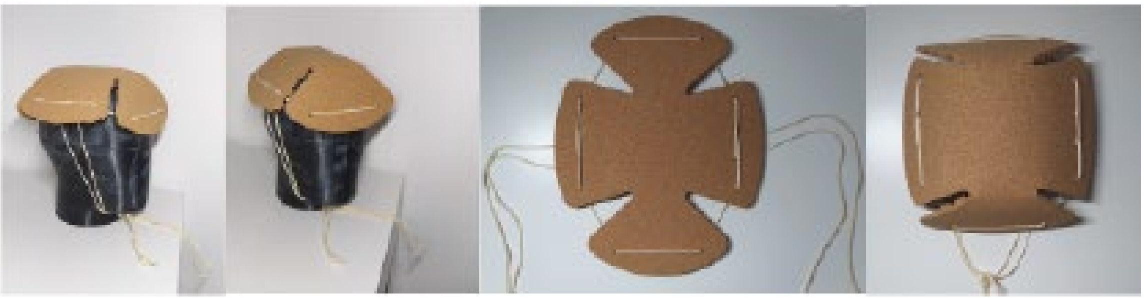


Fig. 63 - More iterations for the final solution

Fig. 64 - Last mock-ups to validate the final concept

6. The final product

The final design proposal resulted from the many iterations that have been made and successfully translated the pursuit of making a convenient helmet that can be flattened to about the size of a laptop (***Fig. 67 and Fig. 68***) and easily fit into a backpack. Such feature is completely new amongst head protection equipment, making this solution very unique. Furthermore, the use of cork as a helmet's liner is also another innovative aspect of the proposed solution. Not only in a functional and aesthetical way, but also concerning sustainability since this concept has a 42% lower carbon footprint than the average bicycle helmets in the market (more details about its sustainability will be discussed next). The concept behind this helmet is aligned with the electric micromobility’s one: to be a practical solution for anyone, be accessible and also a less polluting and more sustainable alternative.

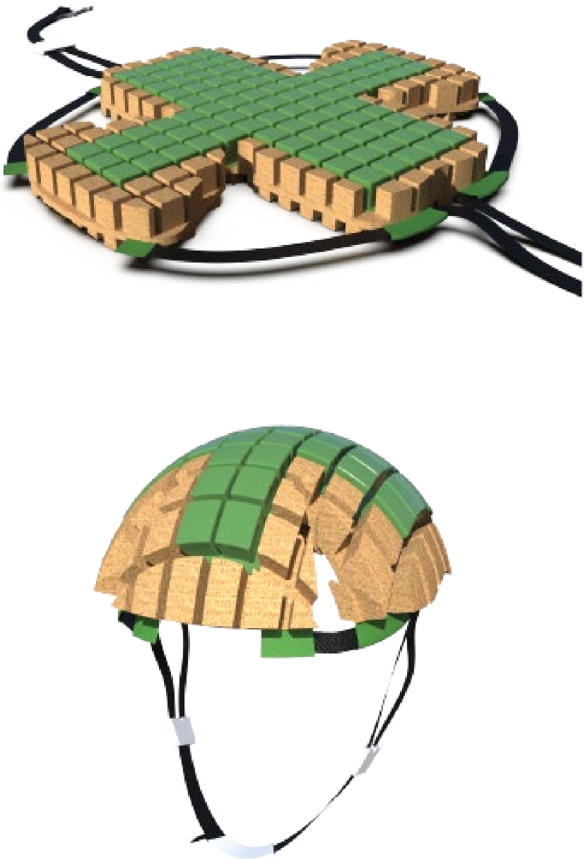


Fig. 65 - Renders of the final concept: Upper image is the flattened helmet; lower image is the conformed / in use helmet

Fig. 66 - Render of the helmet conformed to a person's head

Fig. 67 - Helmet size compared to a laptop’s

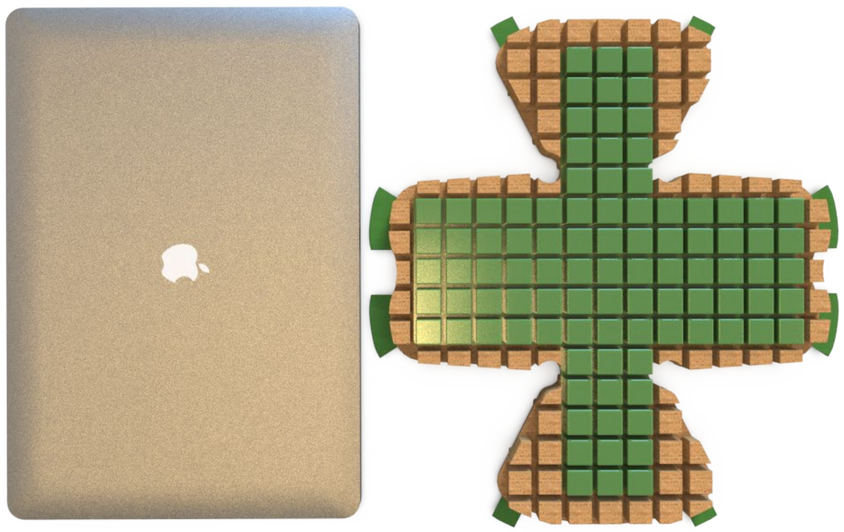


Fig. 68 - Helmet placed side by side with a laptop

6.1. Product's specifications and composition

The helmet is comprised by an outer shell made of TPU, a liner consisting of two cork agglomerate parts (one 20mm and the other 10mm thick) glued to a PET fabric that stands in between them, and the retention system that includes nylon straps and buckles for tightening and fastening the helmet. The constituent parts can be seen in ***Fig. 69***.

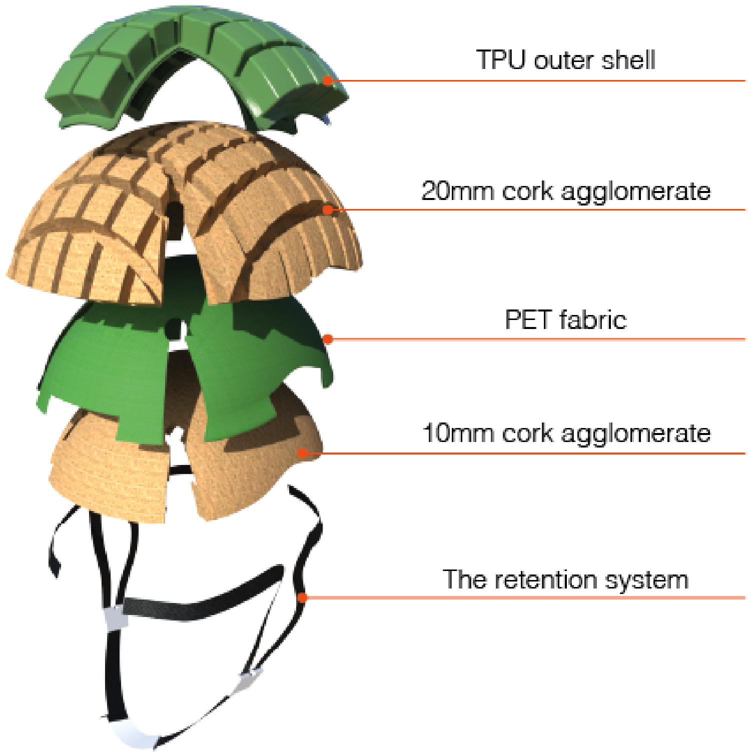


Fig. 69 - Exploded view of the helmet

Its overall dimensions when flattened are about 345 x 293 x 30 mm (LxWxH) and they are precisely represented in ***Fig. 70***. Regarding the device's weight, it is not possible to determine the exact total amount because the accessory parts like the nylon straps and buckles have not been completely defined at this point. However, based on calculations involving volume and density of parts that have already been defined, such as the outer shell, textile, and liner, it was possible to determine that these parts altogether would weight 300 grams. And based on the experimental campaign, the amount of shear thickening fluid to be encapsulated between the cork agglomerate and the TPU can be of about 15% of the mass of these materials combined. Considering that the cork and the TPU together weight about 280 g, that implies in 42 g of STF. Adding that to the fabric would leave a total of 342 g. Therefore, when taking into consideration the buckles and the nylon straps, the overall weight should be slightly below 400 g, which is the average weight for existing foldable/collapsible helmets in the market. A weight comparison can be seen in ***Fig. 71***.

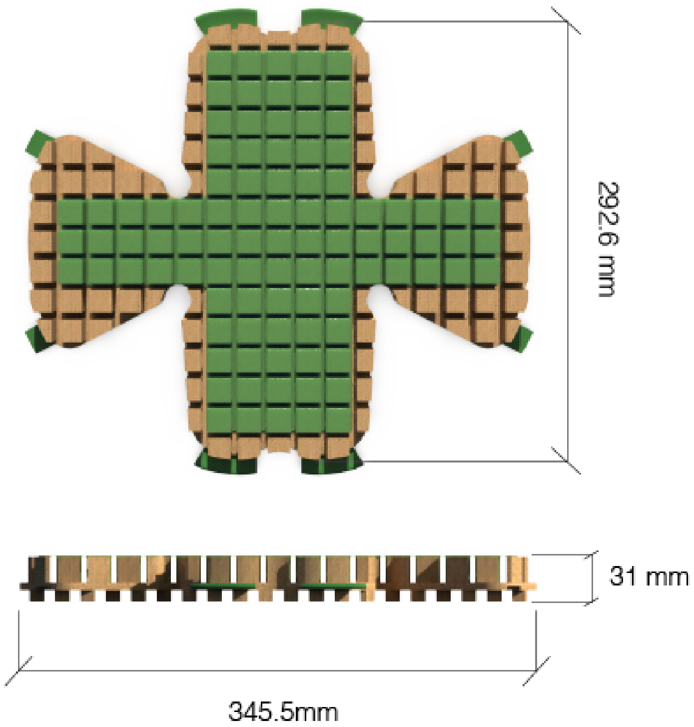


Fig. 70 - Helmet's dimensions when flattened

Fig. 71 - Weight comparison amongst foldable/collapsible helmets

6.1.1. Outer shell

The outer shell (or layer) is made of TPU with an 8mm wall thickness. The fact that this is a quite flexible material, which helps the helmet conform to the head, but at the same time still has good ductile properties, makes it an interesting alternative for this application. Especially when taking into consideration that the hard shell of average helmets, usually made of PC or ABS, are very thin (around 0.3 to 0.5 mm) and consequently have negligible load spreading ability (Mills & Gilchrist, 2003). The part is manufactured through injection molding.

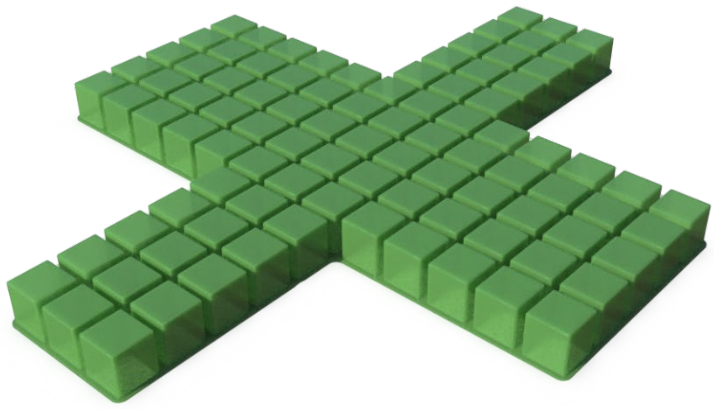


Fig. 72 - TPU outer layer

To help improve the impact force mitigation, an amount of the shear thickening fluid is inserted into each one of the squares (***Fig. 73***). The whole part will be then joined with the cork agglomerate through pressure. The tight fit between the parts once they are joined together makes it very difficult to manually pull them apart (in case any user tries to do so). However, the parts can be later separated for recycling.

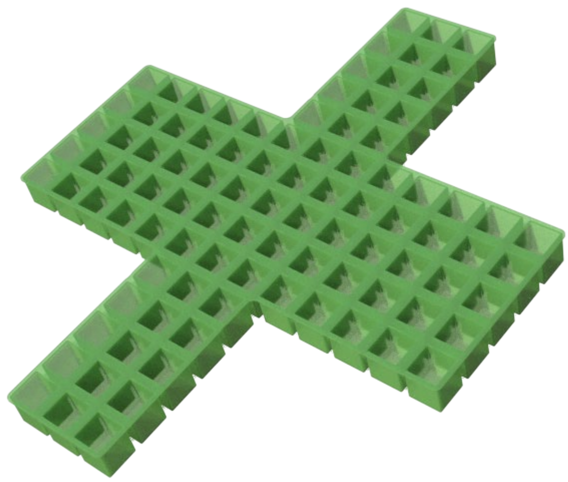


Fig. 73 - TPU layer upside down showing the squares where the STF is placed

6.1.2. Liner

The liner is the most important part of the helmet in terms of performance since it is responsible for absorbing the impact energy, therefore transmitting less force to the user's head. This concept's liner is comprised of three pieces of two materials: two pieces of cork agglomerate of 180 kg/m^3, one 20 mm and the other 10 mm thick, and one piece of PET fabric that stands in between the agglomerates (***Fig. 74***).

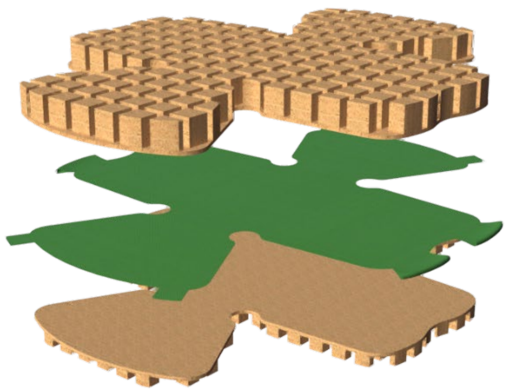


Fig. 74 - Liner's composition

The cork agglomerates are cut in a CNC and their patterns are different from each other. The 10mm thick part is the one that is in contact with the user's head, so when the helmet gets conformed to the head, the face with the cut patterns is subject to compression forces, which will make the squares get closer to each other. The opposite happens to the 20mm piece of cork, which is subject to traction, making the squares go away from one another. Therefore, to deal with these different acting forces and to achieve an optimal shape when conformed to the head, the cut's width and distance was designed differently. While the cuts in the 10 mm thick part are 10 mm wide and also 10 mm apart from each other, the ones in the 20 mm thick part are 5 mm wide and 15 mm apart (***Fig. 75***).

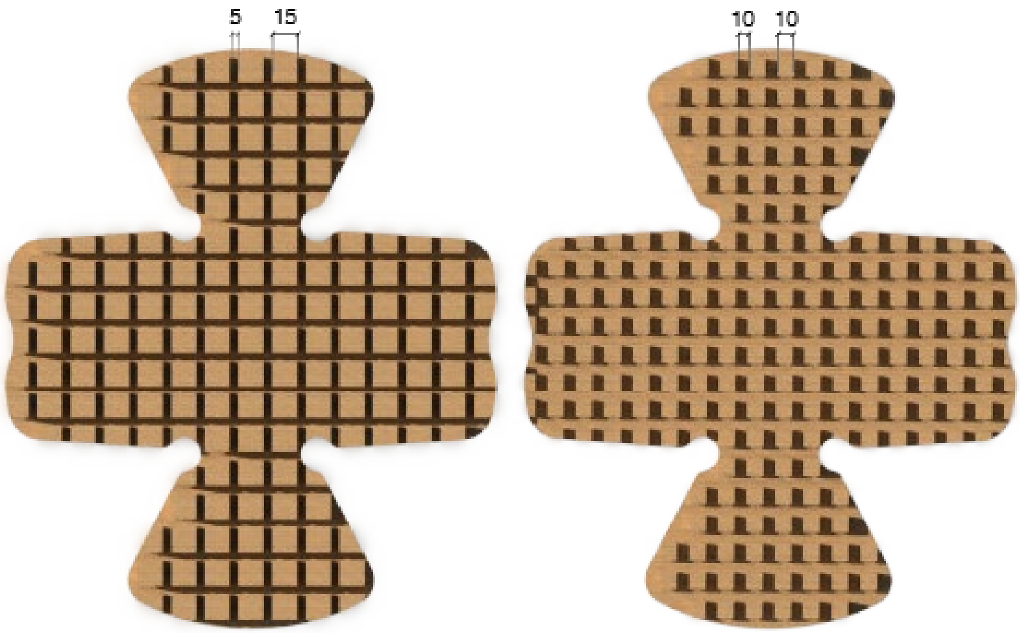


Fig. 75 - Different cut patterns and its measurements. On the left, the 20mm thick part; on the right, the 10mm

As for the PET fabric that stands in between the cork agglomerates, it has the function of holding the parts together and giving it more flexibility, besides also being responsible to connect the liner with the retention system since it is where the nylon straps are sewn to and where they pass through. The PET fabric is itself a recycled material from PET bottles, process which does not consume much energy. The material is not only very resistant and long-lasting but also can be easily recycled after its use.

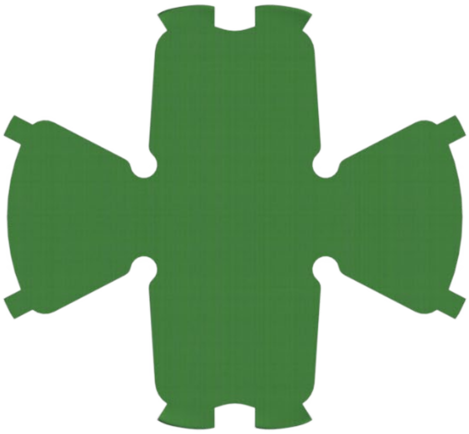


Figure 76 - PET fabric's shape

6.2. Life Cycle Assessment (LCA)

Since the beginning of the process the sustainability of the final solution was one of the main objectives. In order to verify if the goal was achieved, it is necessary to assess the final product's environmental impact in measurable way, and the best manner to quantify a product's impact is through the amount of greenhouse gases (GHG) emitted. Very accurate and detailed LCAs take into consideration many aspects of the product's life cycle, for instance the material extraction, how this material is transported to the factories, where the factories are located, energy consumption of manufacturing processes, type of energy used, transportation to the vending sites and many other associated with the end of the life cycle. Nonetheless, for this particular study just the direct influence of the material and the energy consumption of the manufacturing processes involved in the production of the parts were considered. Transportation of raw materials and delivery from factory to retailer or client are not accounted for. The main purpose of this study is to simply verify, in a broad spectrum, if the proposed solution does in fact reduce the level of emissions in comparison to what is currently being manufactured.

In order to obtain all the necessary data regarding all the variables, it was necessary to resort to a few different sources: the carbon footprint of the materials in $KgCO_2eq$ and the energy consumption, in KWh, of each of the manufacturing processes involved were extracted from the 2030 Calculator (2020); to convert the electrical consumption into GHG emissions, a formula given by Carbonfund (2021) was used; since there are few data available regarding the carbon footprint of white cork agglomerate, the values obtained by Sierra-Pérez et al (2016) in their study were used as a reference; lastly, the work from Correia (2019) was used as a reference to obtain the GHG emission values regarding the machining of cork with a CNC.

Table 11 shows a comparison between the carbon footprint of an average bike helmet and the solution presented in this work. The total emission of the average helmet is 1.30 $KgCO_2eq$ against 0.755 $KgCO_2eq$ of the concept. That represents a total of 42% reduction in GHG emission. This reduction could probably be higher, given the fact that cork is able to sustain multi-impacts and be recycled, unlike its synthetic counterpart. However, these numbers could not be calculated in this study given the lack of available resources to use. In consideration to the carbon footprint value used for the cork (-0.04 $KgCO_2eq$), which represents a negative footprint, it considers the biogenic carbon – originated from biological sources such as plants and soil and represents a great potential for GHG emissions. If not considering the biogenic carbon, the value for the cork agglomerate would be 0.02 $KgCO_2eq$. Also for the TPU, it was considered the use of a “green TPU”, a version of the material that uses CO_2-based polyols for the polymeric syntheses of the thermoplastic, procedure which can reduce up to 20% the global warming potential of the TPU and has become very prominent in the polymer industry (Alagi et al., 2017; Von Der Assen & Bardow, 2014). However, even if the cork’s biogenic carbon and the “green TPU” are not considered, the resulting total emission would be 0.955 $KgCO_2eq$, which would still represent a reduction of 26.5% in GHG emission.

Table 11 - LCA comparison between an average helmet and the proposed solution

	Part	Materials					Processing			Total KgCO2eq.
		Type	Volume (mm³)	Density (kg/m³)	Mass (g)	Total KgCO2eq.	Process	Energy consumption (KWh)	Total KgCO2eq.	
AVERAGE BIKE HELMET	Liner	EPS	2.065 E+06	100	206	0.9	"Injection" Molding	0.0345	0.015	1.30
	Outer Shell	PC	4.3576 E+04	1200	50	0.38	Thermo-forming	0.02	0.0085	
	Accessories	Straps & buckles	Not considered in this study							
FINAL PROPOSED SOLUTION	Liner	Cork	1.35 E+06	180	186	- 0.04	CNC	-	0.04	0.755
	Outer Shell	"Green" TPU	8.079 E+04	1235	100	0.544	Injection Molding	0.03	0.012	
	Textile in between cork	PET	-	-	30	0.170	Weaving	0.022	0.009	
	Shear thickening fluid (STF)		Not considered in this study							
	Accessories	Straps & buckles	Not considered in this study							

It is important to mention that in order to calculate the weight and volume of each of the helmets’ parts, volumetric data from the respective CAD models (1:1 scale) was used. For the concept presented in this work, the CAD was the one developed by the author, and to represent the average helmet it was a model available at GrabCad (2021). Despite the latter being true to size, the obtained data can only be considered an approximation of what the volume of a standard helmet would be. A top and side view comparison of the two models can be seen in ***Fig. 77.***

Fig. 77 - Helmet models used to obtain volumetric data for LCA comparison. On the left, the concept's model and, on the right, the model from GrabCad (2021).

The helmet's concept here demonstrated addresses three of the seventeen goals established by the United Nations 2030's sustainable development agenda:

- Goal number 3 – Good health and well-being: By developing a more convenient helmet for the user of micromobility, the aim is to stimulate a more frequent use of the protection device and help reduce the rising number of accidents and injuries.
- Goal number 12 – Responsible consumption and production: Through replacing synthetic foams by natural materials, using this material's resistance to multi-

impacts to extend the product's life, and designing for ease of disassembly and recycling.

- Goal number 13 – Climate action: 42% less carbon emissions when compared to the standard bike helmet in the industry thanks to the choice of materials, the possibility of easy disassembling the components and its consequent recycling and reintroduction in the manufacturing process.

Fig. 78 - UN sustainable development goals met by the helmet's concept

6.3. Design for Manufacturing (DFM) & disassembly

One of the design intentions was to make the product accessible for manufacturing, meaning that it could be produced using more accessible technology. For the liner, i.e., the two cork agglomerate parts, a simple CNC machine with only three axis is enough for the production. Therefore, there is no need for expensive tooling and machinery that, besides being costly, also consume more energy. Another advantage of CNC manufacturing is the possibility of producing parts of many different sizes (to fit different head shapes) without the need of investing in a variety of molds, which would be the case for injection molded or thermoformed parts. This possibility could be interesting for helmet manufacturers if considered that current headforms used in standards impact tests may not represent the cyclist's head shapes (Thai et al., 2014). The fact that the helmets must be developed to meet the standards on ISO-related headforms, creates a difficulty (logistical and, especially, financial) for them to offer greater range of sizes. This concept is flexible enough to adapt to different business models, which means that it can either be used in a mass sharing perspective (one size fits all) and be attached to the shared e-scooters, or it can serve a more individualistic purpose through rental, subscription or even purchasing, which would allow for a broader range of sizes to be offered.

Besides the ease of creating many helmet sizes, the manufacturing method also allows for a variation of the cutting patterns, which could ultimately create the possibility of developing different shapes. However, different shapes, such hexagons for instance, could affect the overall manufacturing time and eventually not be cost effective. The actual regular pattern of a square grid has been designed to optimize the CNC operation as well as to conform better to the head. Different shapes are possible but need to be carefully studied before being implemented. In a simulation run with Solidworks CAM, the estimated time to machine one single part (20 mm thick) is about 5.7 minutes (***Fig. 79***). This is a rough estimation since cork is not part of the software's' material library and the simulation was done as if the material was a polyurethane of about the same density. Therefore, tuning of settings, such as tool's feed rate and rpm, may be needed, which could result in a longer or shorter machining time. Moreover, the overall time can be further optimized when cutting several pieces in a standard cork agglomerate board (***Fig. 80***).

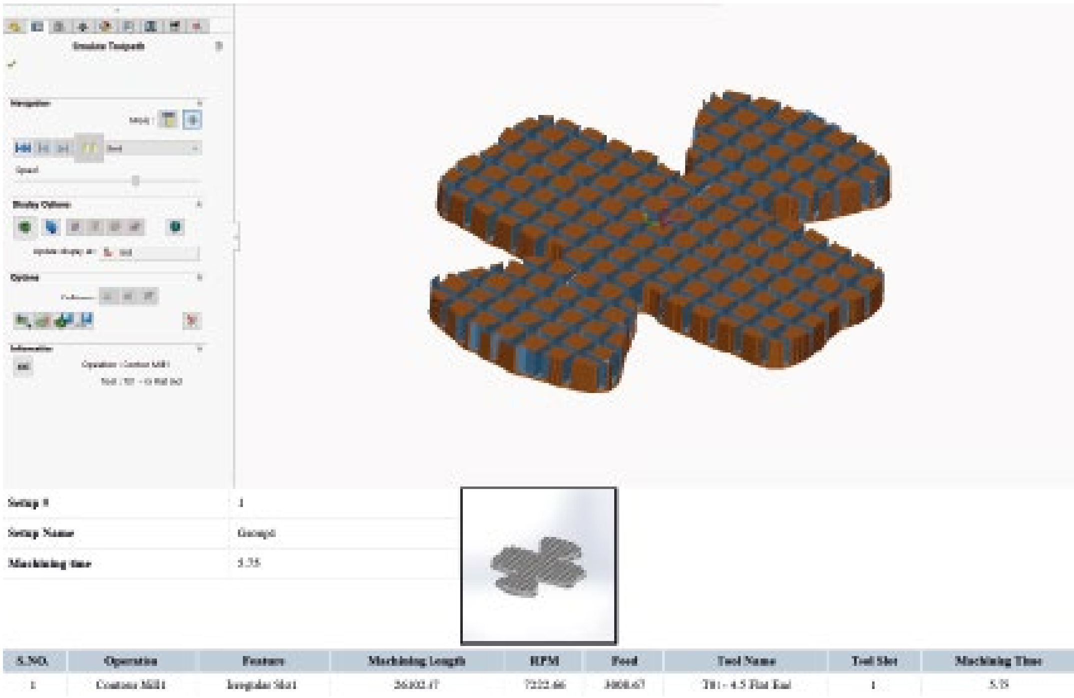


Fig. 79 - Machining time simulation in Solidworks CAM

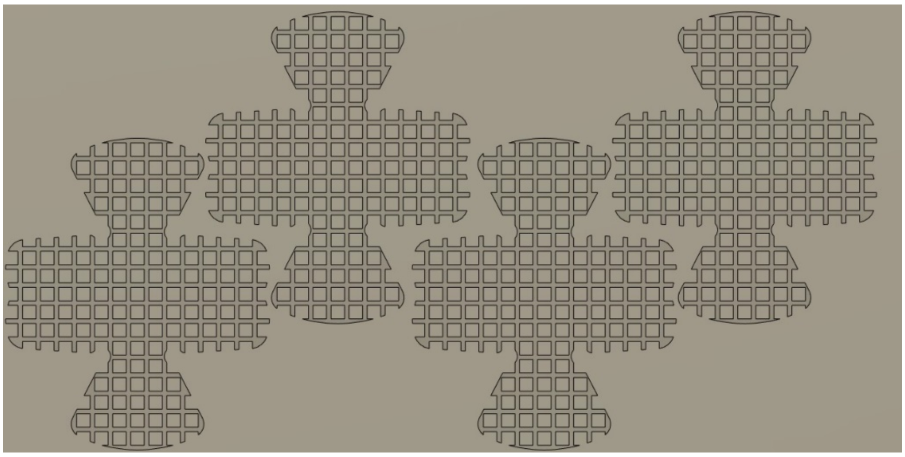


Fig. 80 - Representation of a possible cutting scheme in a 1000 x 500 mm cork agglomerate board

In the perspective of a one-size-fits-all model, in order to perhaps increase the production's volume and speed, there might be a need to shift the manufacturing process to a molding process, where the cork would be already conformed to the shape of the helmet without the need of going through a subtractive manufacturing. This is a possibility but would otherwise affect the LCA study presented in the previous section of this document and, just like for the production of different shapes, further studies and analysis would be necessary before implementing it.

The helmet is designed with the purpose of being separated by material in order to enable the recycling of all its components, unlike the current standard helmets that usually have their hard shells fused with the EPS foam because of the in-mold injection. The cork agglomerate can be reprocessed and recycled into new boards and products without losing its properties. The fact that TPU is a thermoplastic makes it completely recyclable, however its mechanical properties, mainly the tensile strength, decreases after every recycling cycle (Wölfel et al., 2020). Regarding the STF, to the author's knowledge there is no available data about the recycling of such materials. Nonetheless, because the material never cures and always remains in a viscous state, it can be washed and therefore separated from the TPU and cork.

7. Conclusion & final remarks

The electric micromobility is a very recent phenomena and is expected to grow much more until 2030. The problems and advantages associated with its use in large metropolitan areas are only starting to be fully understood, which leaves room for new solutions that can improve the overall experience of renting an e-scooter.

The product development process is long, has many steps and many variables to consider. This work went deep in the research phase in order to understand the challenges and problems faced by the EMM sector in different parts of the world concerning legislation, type of users, frequency of use, helmet usage, sustainability, among others. Furthermore, it analyzed all the aspects of a helmet, its materials and respective functions, what are the options offered in the market as well as the standards responsible for testing and certifying the helmet's efficiency in terms of protection.

Literature has also been thoroughly revised in search for material alternatives to what is currently being used in the helmet industry with the intention of exploring a completely new and innovative solution for the application. With the indication that cork and shear thickening fluids were promising materials for shock absorbing applications, experimental campaigns consisting of drop impact tests have been made with a variety of material samples provided by Amorim Cork Composites and Polyanswer in order to find the best and most suitable materials. After the material selection through analysis of peak forces, energy dissipation, duration of impact, maximum acceleration and strain levels, a numerical validation was carried in Abaqus so that an FEA simulation of a helmet standard's impact attenuation test could be done using the same software in order to verify if the tested materials would eventually comply with the standards and what would be the optimal thickness to work with. The next steps were about working with the material, cork, in order to perceive how it could conform to a person's head and fulfill the design intention. It took many iterations and findings to validate the idea and propose a helmet concept that successfully incorporated the tested materials.

The proposed solution meets the priorly established design intentions of incorporating natural materials to replace the synthetic foams, being able to flatten and conveniently store it in a backpack/bag, and disassociating its components to fully recycle them by the end of the helmet's life cycle. The combination of materials and processes used in this solution and the functional aspect of being able to completely flatten, bring a big scope of innovation to the head protection's sector. Moreover, the more convenient helmet for micromobility users aims to facilitate and stimulate its use in times where the number of accidents and serious injuries are reaching record numbers.

Many competences have been acquired throughout the long design process, such as concepts related to the dynamic impacts and how to work with FEA in Abaqus. Regarding the project's methodology, it was also the first time testing materials' mechanical properties to define design constraints and restrictions. The project was a good opportunity to involve both disciplines, design and engineering, and learn in a practical way how to combine them in the product's development.

7.1. Future works

Despite the very satisfactory final result, it is important to recognize that it could not address everything. Many aspects of the product still need to be explored, like is the case of ergonomics and the helmet's integration with the sharing systems. Both are correlated and are reliant on the definition of the business model, which would require a thesis on its own. For instance, business models based on providing helmets through subscription or rental via vending/distribution points could perhaps be able to serve the users in a more individualistic way by offering a greater range of helmet sizes. On the other hand, if the model is based on renting the helmet with the e-scooter, the size of the equipment would have to be more generalist, probably based on an average head size that represents the 50% percentile of the population. The concept is flexible enough to adapt to both options, however further investigation and studies would be needed to justify the choice and properly implement the solution. The same is true in relation to the production costs that were not possible to calculate within the scope of this project.

Beside the topics that need a more in-depth analysis to be implemented, others could not be included in this work due to the lack of time. This is the case of the numerical validation of all the materials used in the final concept, including the STF, and the consequent simulation with finite elements of how the proposed helmet would perform in the impact attenuation test. The production of a final prototype and to make it undergo a drop impact test would also be another interesting step to realize. Finally, still in the realm of impact simulations, it would be necessary to test the helmet for impacts in multiple regions and different impact surfaces, as stated in the current standards, like the top, sides, front and back. This analysis is important due to the differences caused by the head's moments of inertia in the acceleration of the headform, leading to different results depending on the area of impact.

Overall, the final design is a unique and innovative product in many aspects from aesthetics to functionality and sustainability. This solution has plenty of room to be optimized and further developed, however it can already be considered a one of its kind pioneering solution in the helmet industry.

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Attachments

PRODUCT SPECIFICATION

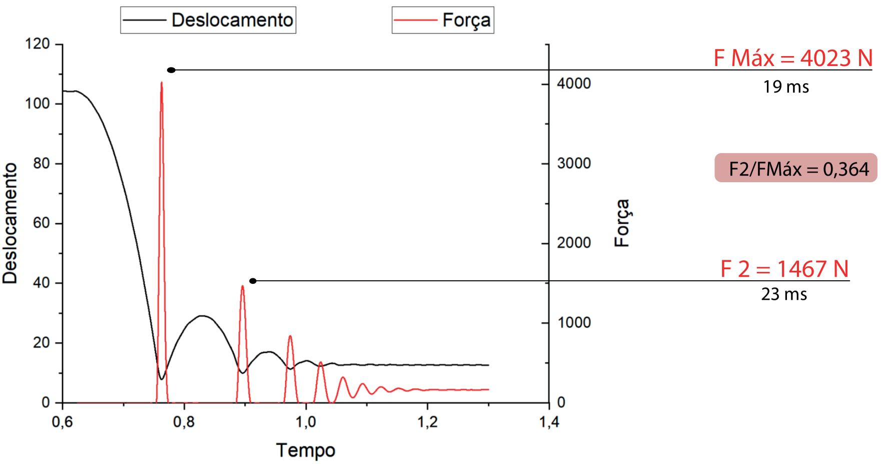
8003

Binder	Polyurethane
Colour	Natural
Cork Granule Size	0.5/1 mm

TEST METHOD	PROPERTY	UNIT	VALUE
ISO 7322	Specific weight	Kg/m^3	170 - 240
ISO 7322	Tensile strength	kPa	≥ 400
ISO 7322	Compressibility	%	30 - 50
ISO 7322	Recovery	%	≥ 75
ISO 7322	Boiling water	-	No disaggregation

PDA02007/8

CORTIÇA 5MM + FLUIDO + CORTIÇA 5MM (C5-F-C5)



Massa total = 9.72 g

Massa do fluido = 4,76 g

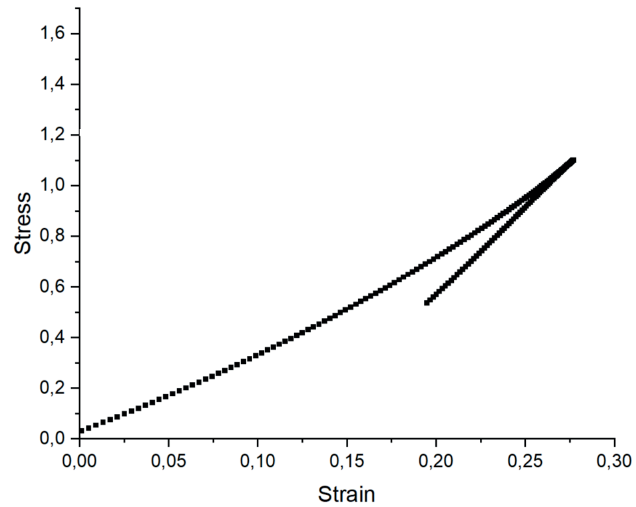
Espessura = 10.8 mm

Área = 2500 mm²

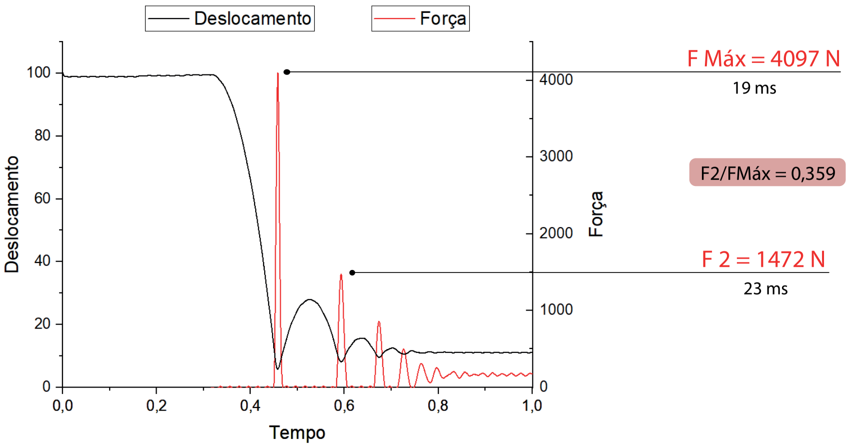
Energia de impacto: 20J

σ Máx = 1,61 MPa

ε Máx = 27.69 %



CORTIÇA 5MM + CORTIÇA 5MM (C5-C5)



Massa total = 4.80 g

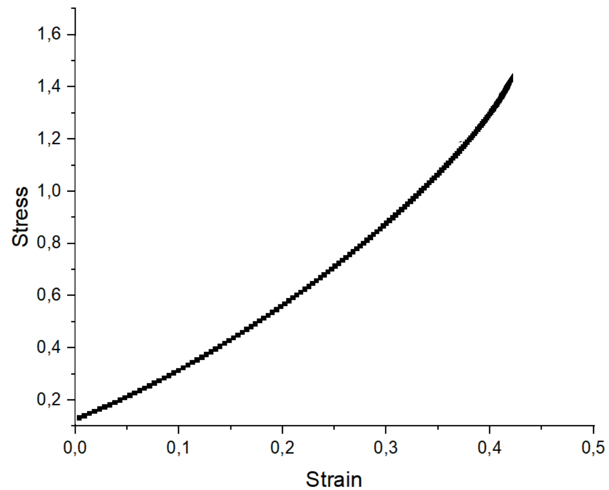
Espessura = 10 mm

Área = 2601 mm²

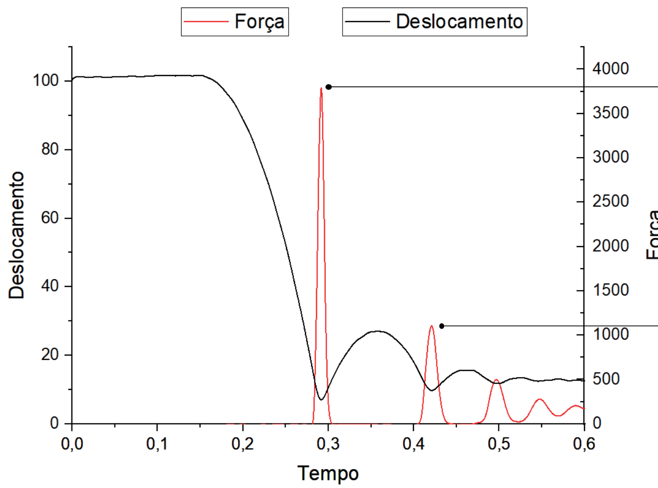
Energia de impacto: 20J

σ Máx = 1,57 MPa

ε Máx = 42.1 %



CORTIÇA 10MM + TECIDO IMPREGNADO (C10+TI)

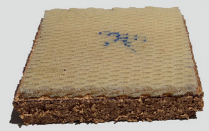


Massa total = 5,80 g

Espessura = 14,15 mm

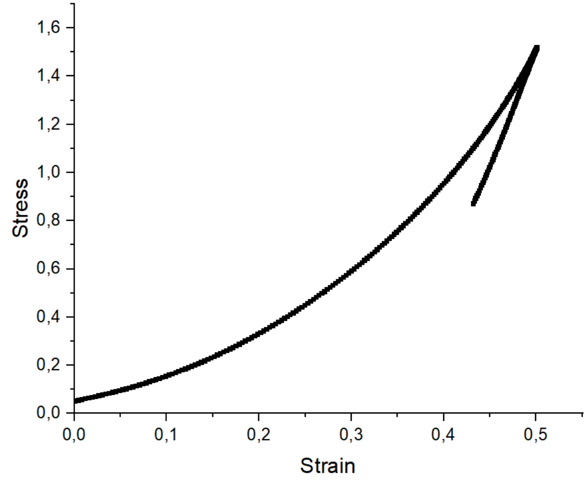
Área = 2495 mm²

Energia de impacto: 20J

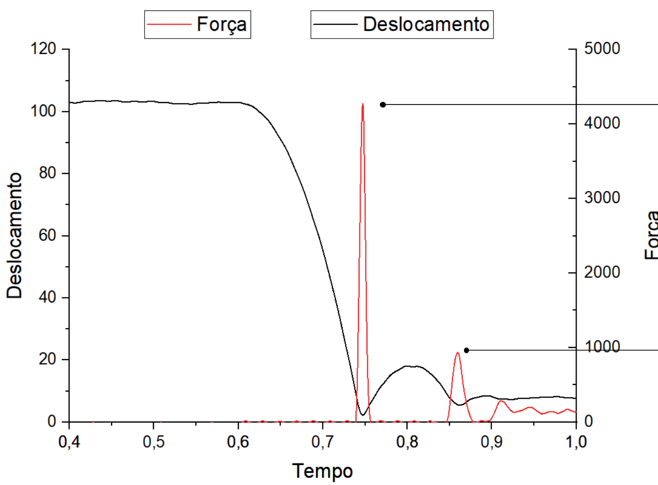


σ Máx = 1,52 MPa

ε Máx = 50.13 %



CORTIÇA 10 MM (C10)



Massa total = 4,34 g

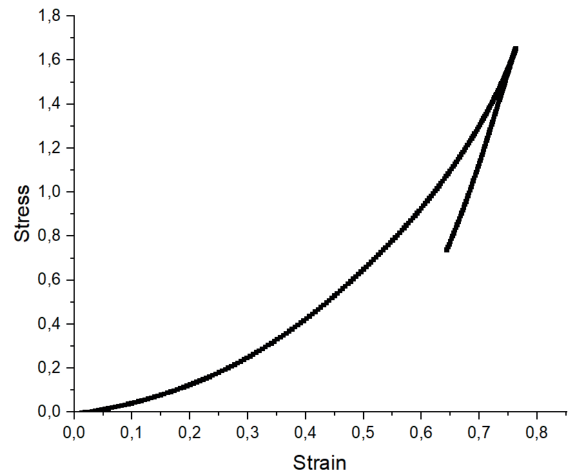
Espessura = 9,65 mm

Área = 2588 mm²

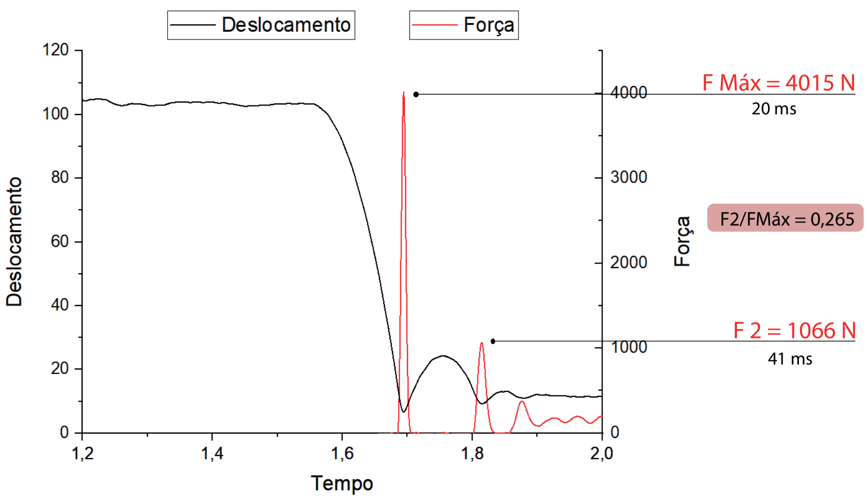
Energia de impacto: 20J

σ Máx = 1,65 MPa

ε Máx = 76.32 %



CORTIÇA 10MM + PVC VERMELHO (C10+PVC)



Massa total = 13,76 g

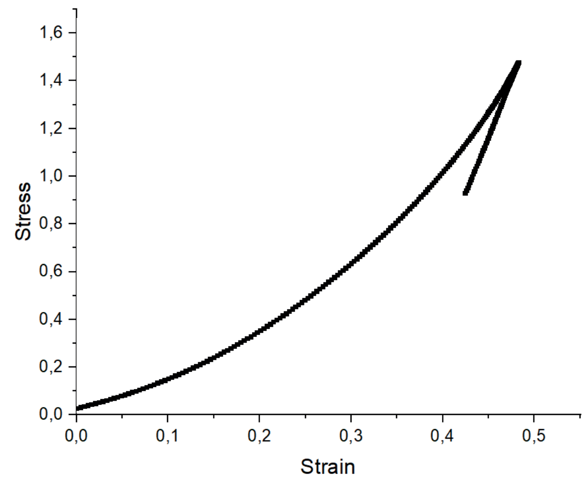
Espessura = 12,95 mm

Área = 2657 mm²

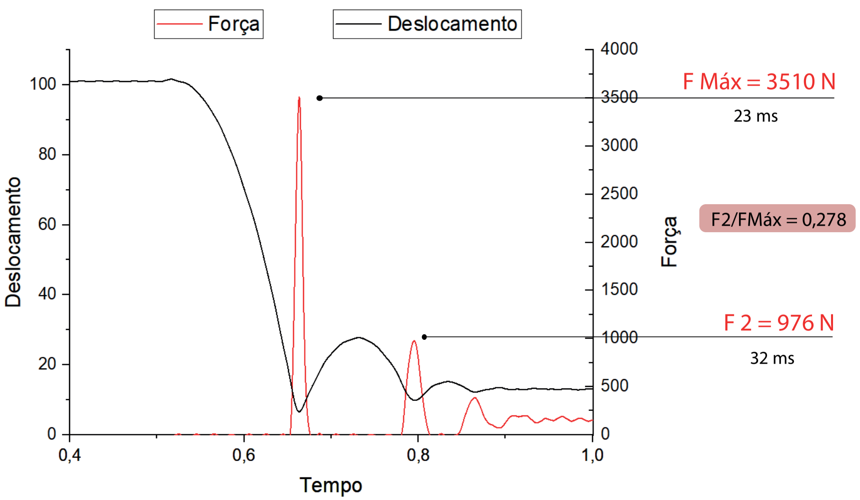
Energia de impacto: 20J

σ Máx = 1,51 MPa

ε Máx = 48.36 %



CORTIÇA 10 MM + BORRACHA PRETA 3,3 MM (C10+BP3.3)



Massa total = 12,94 g

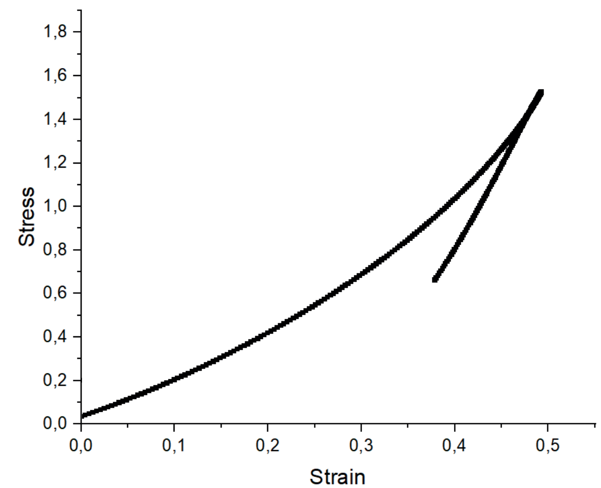
Espessura = 12,95 mm

Área = 2076 mm²

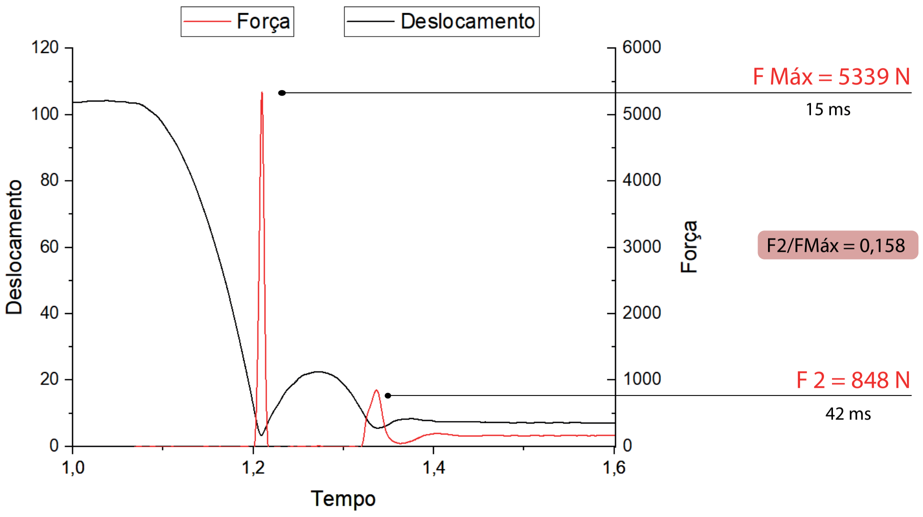
Energia de impacto: 20J

σ Máx = 1,69 MPa

ε Máx = 49.25 %



BORRACHA PRETA 10 MM (BP10)



Massa total = 9,62 g

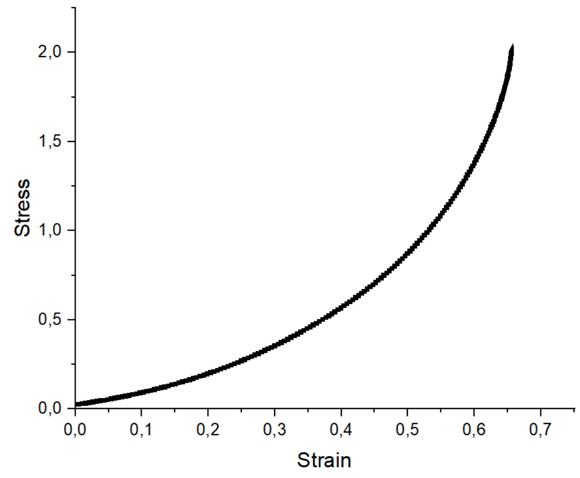
Espessura = 10 mm

Área = 2570 mm²

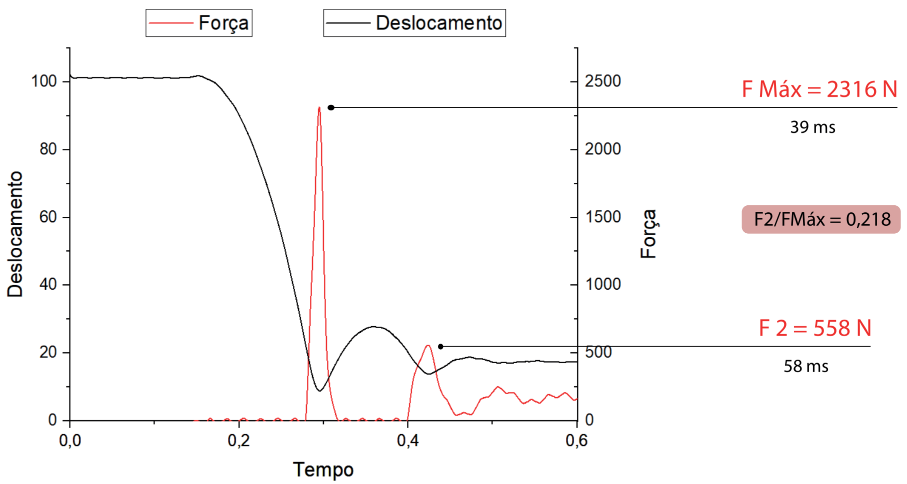
Energia de impacto: 20J

σ Máx = 2,08 MPa

ε Máx = 65.58 %



CORTIÇA 20MM (C20)



Massa total = 4,20 g

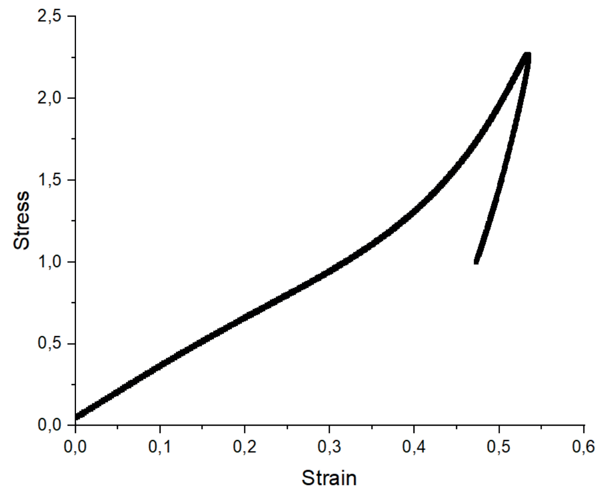
Espessura = 19 mm

Área = 1031 mm²

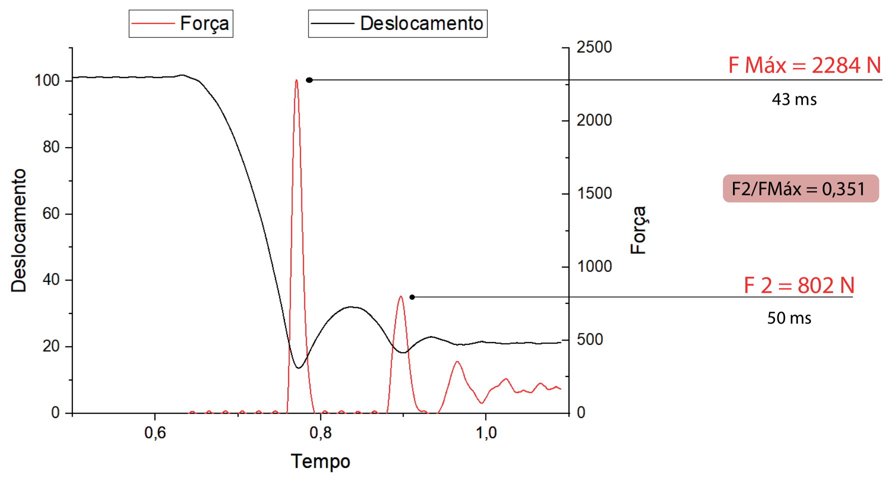
Energia de impacto: 20J

σ Máx = 2,46 MPa

ε Máx = 53.5 %



CORTIÇA 20MM + TPU (C20+TPU)



Massa total = 9,54 g

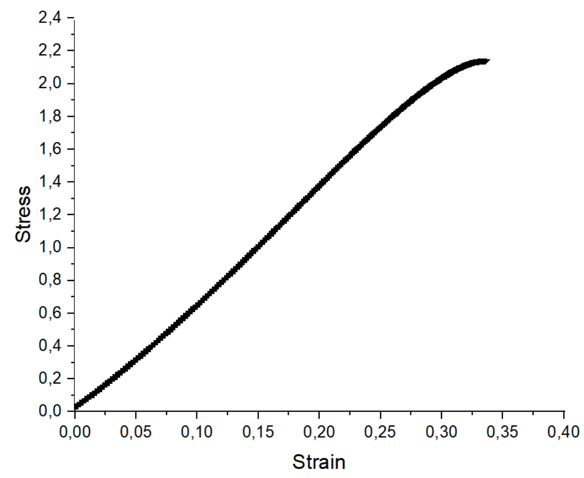
Espessura = 21 mm

Área = 1043 mm²

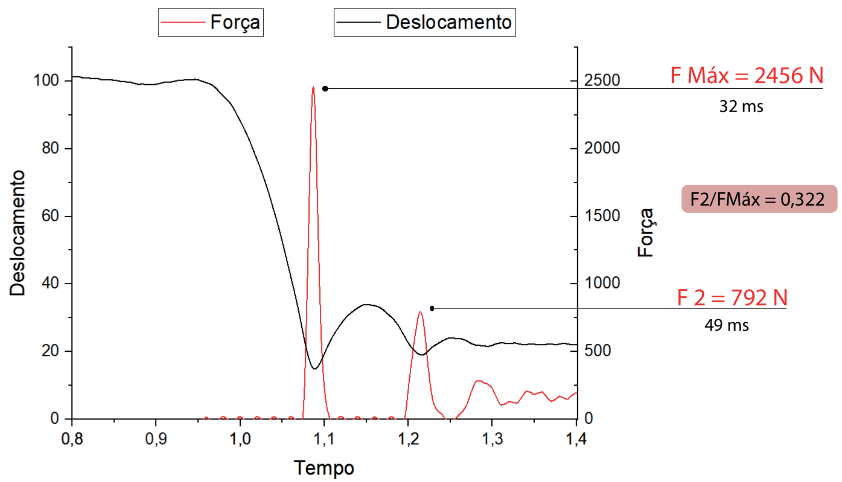
Energia de impacto: 20J

σ Máx = 2,19 MPa

ε Máx = 34.97 %



CORTIÇA 20MM + FLUIDO + TPU (C20-F-TPU)



Massa total = 12 g

Massa do fluido = 2,14 g

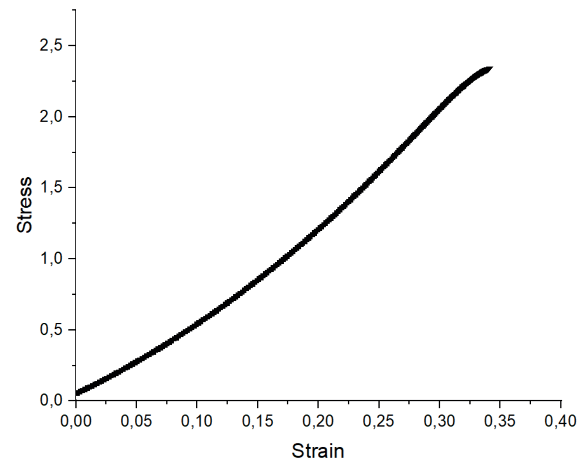
Espessura = 22.9 mm

Área = 1043 mm²

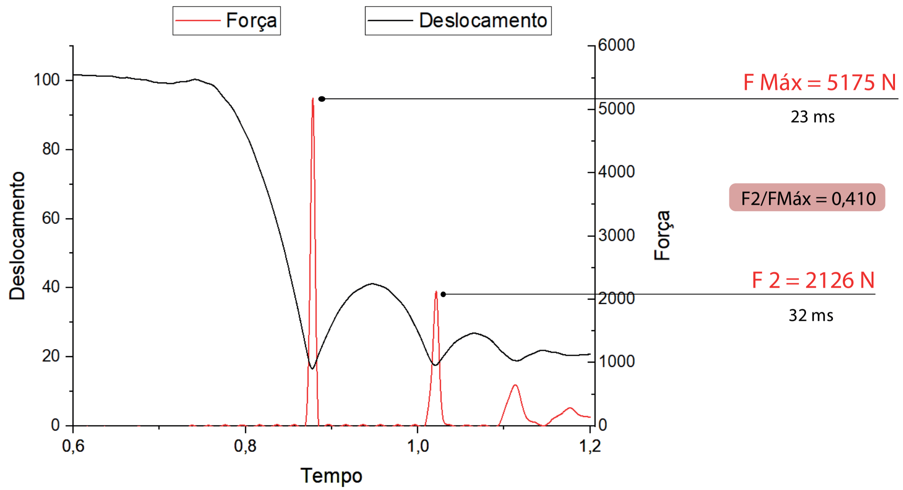
Energia de impacto: 20J

σ Máx = 2,55 MPa

ε Máx = 35.13 %



CORTIÇA 20MM + PLA (C20+PLA)



Massa total = 10,32 g

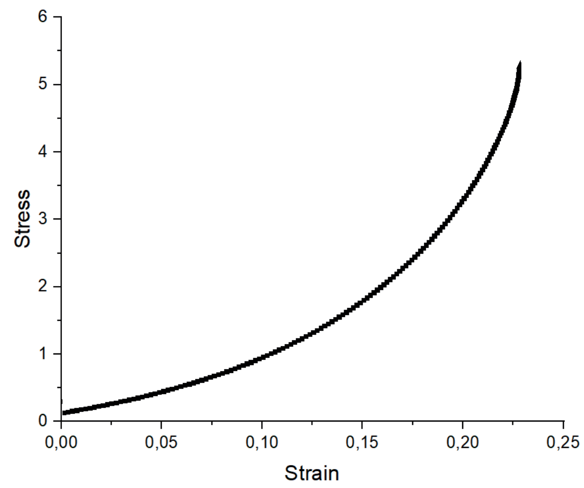
Espessura = 21,50 mm

Área = 928,6 mm^2

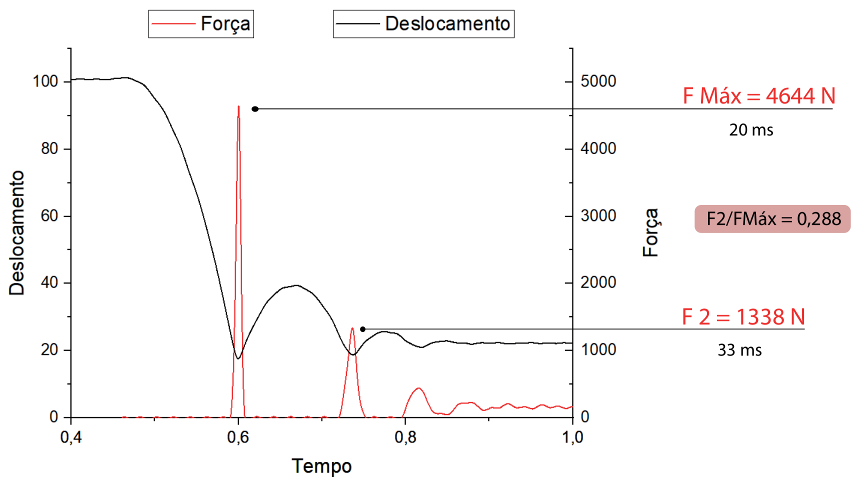
Energia de impacto: 20J

σ Máx = 5,57 MPa

ε Máx = 22.79 %



CORTIÇA 20MM + FLUIDO + PLA (C20-F-PLA)



Massa total = 12,60 g

Massa fluido = 1,80 g

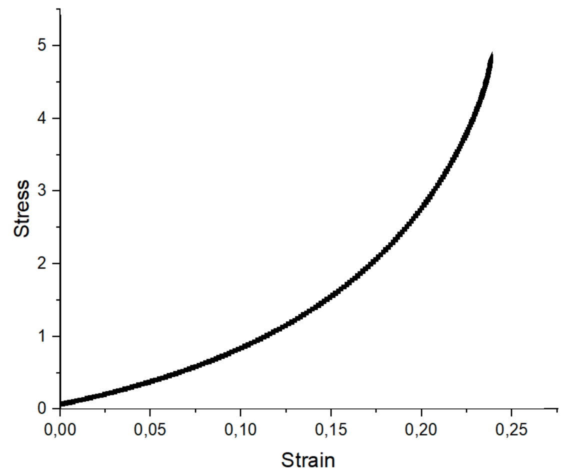
Espessura = 23,10 mm

Área = 928,6 mm^2

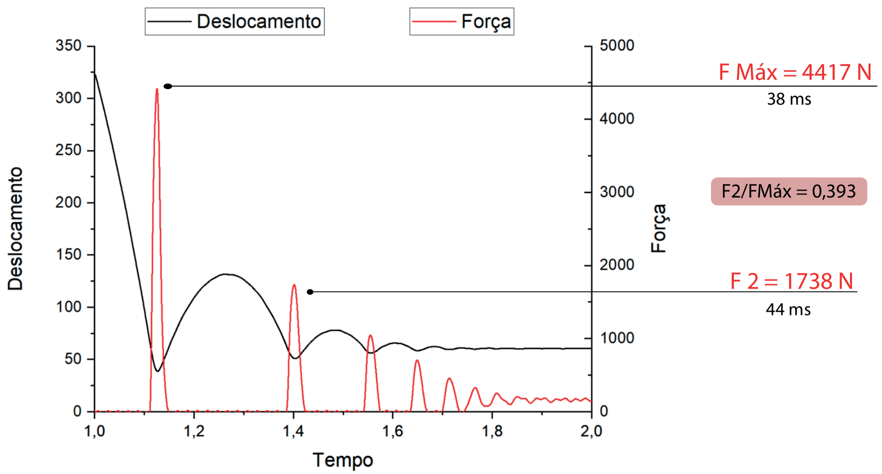
Energia de impacto: 20J

σ Máx = 5,00 MPa

ε Máx = 23.80 %



CORTIÇA 60MM (C60)



Massa total = 44,66 g

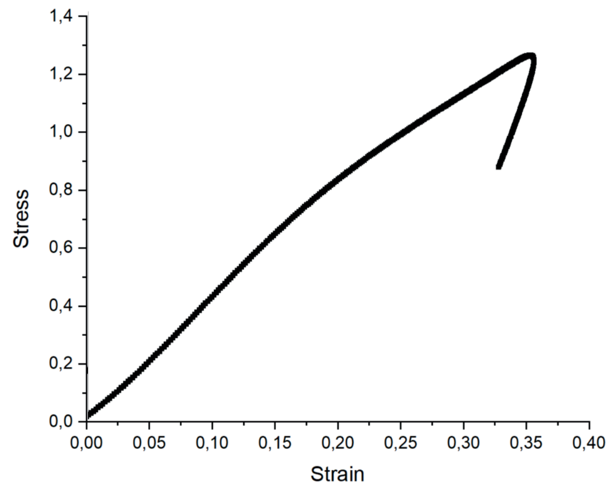
Espessura = 60 mm

Área = 3480,75 mm²

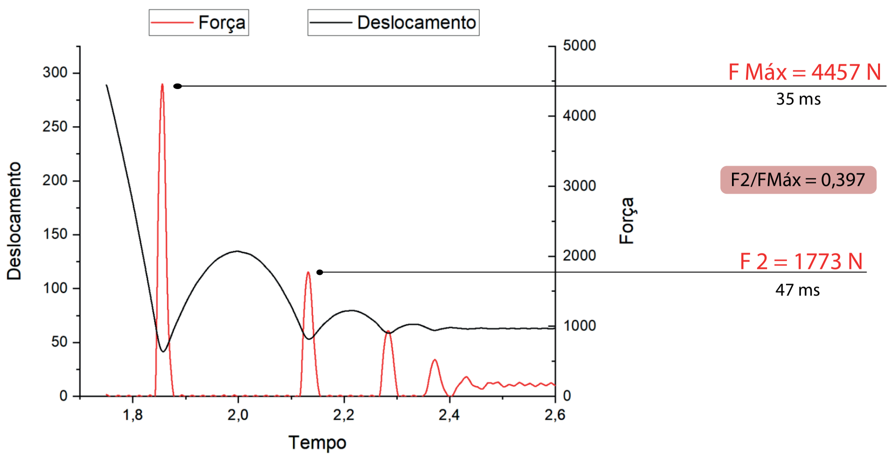
Energia de impacto: 100J

σ Máx = 1,26 MPa

ε Máx = 35.53 %



CORTIÇA 50MM + BORRACHA PRETA 3,3 MM (C50+BP3.3)



Massa total = 50,86 g

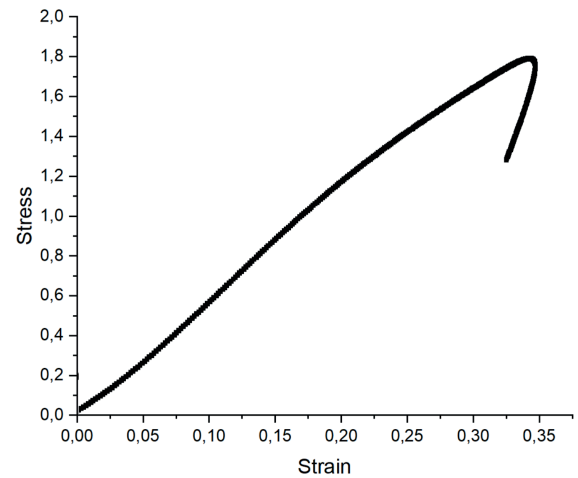
Espessura = 63,30 mm

Área = 2461,87 mm²

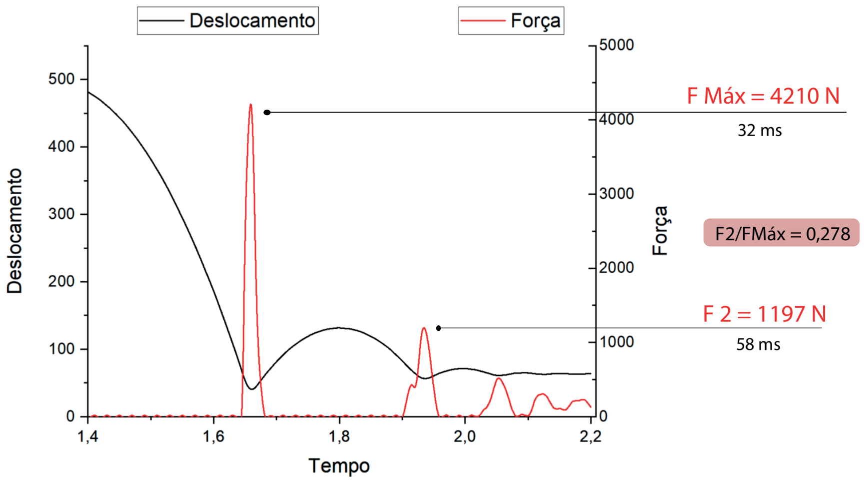
Energia de impacto: 100J

σ Máx = 1,81 MPa

ε Máx = 34.66 %



CORTIÇA 60MM + PVC VERMELHO (C60+PVC)



Massa total = 50.02 g

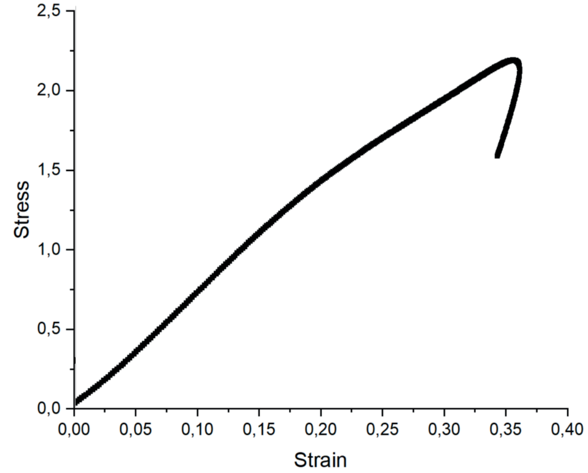
Espessura = 63,30 mm

Área = 1911 mm²

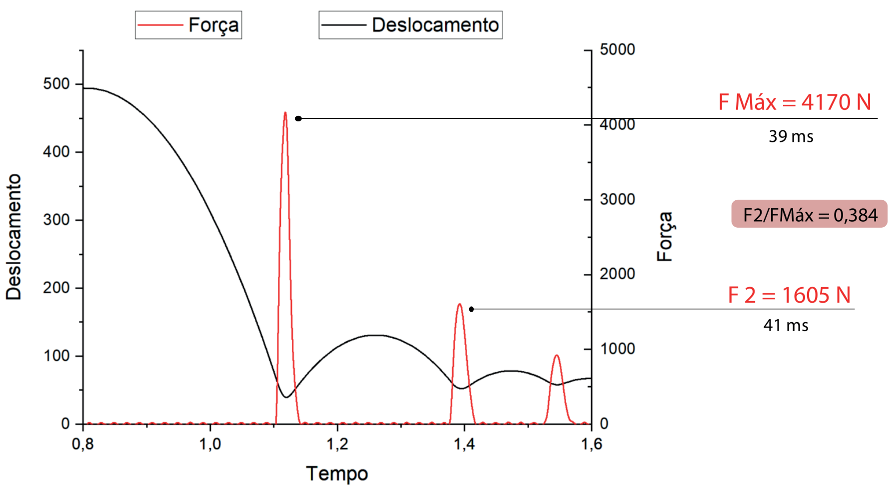
Energia de impacto: 100J

σ Máx = 2,2 MPa

ε Máx = 36.05 %



CORTIÇA 60 MM + TECIDO IMPREGNADO C60+TI)



Massa total = 43,34 g

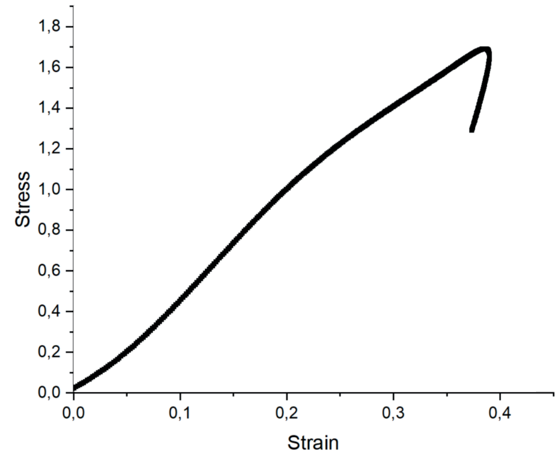
Espessura = 64,5 mm

Área = 2400 mm²

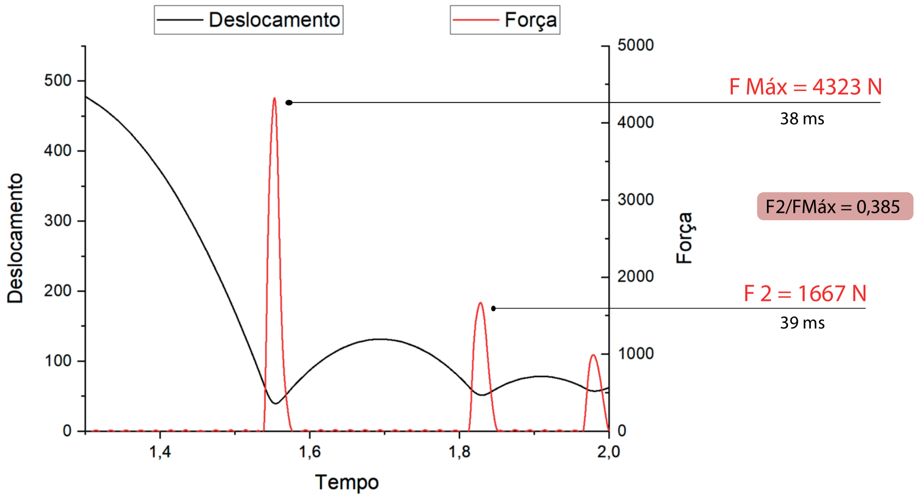
Energia de impacto: 100J

σ Máx = 1,73 MPa

ε Máx = 39.13 %



CORTIÇA 50MM + FLUIDO + CORTIÇA 10MM (C50-F-C10)



Massa total = 47,94 g

Massa fluido = 4,26 g

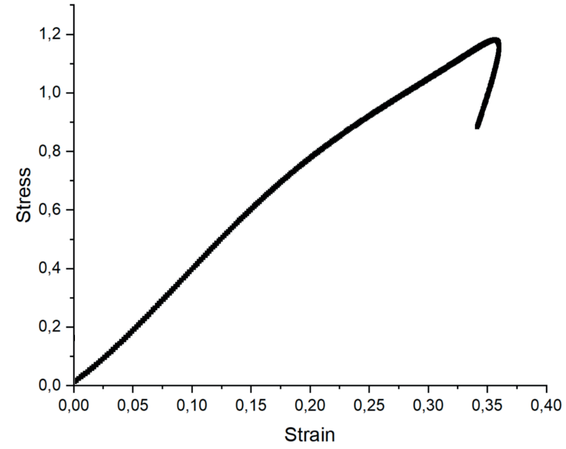
Espessura = 61,5 mm

Área = 3568,5 mm^2

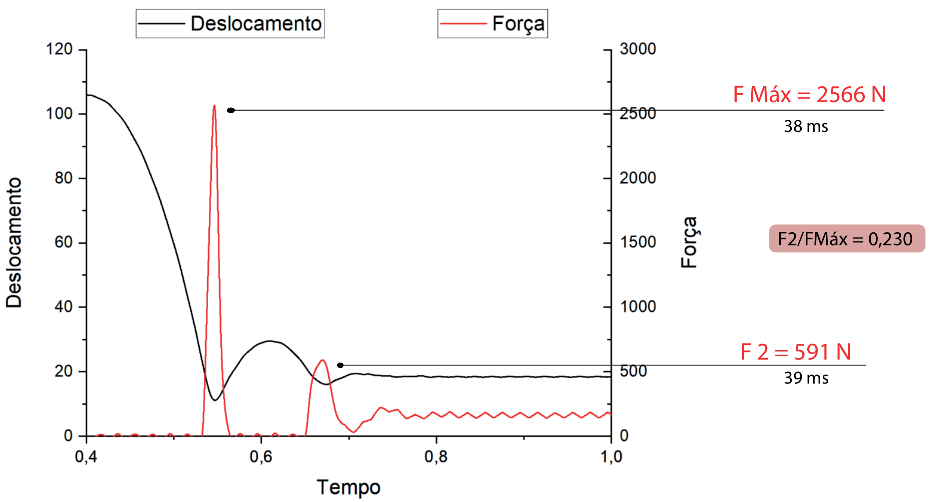
Energia de impacto: 100J

σ Máx = 1,21 MPa

ε Máx = 36.02 %



CORTIÇA 10MM + BORRACHA PRETA 10MM (C10+BP10)

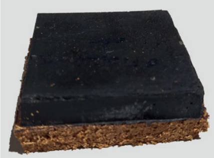


Massa total = 14,48 g

Espessura = 20 mm

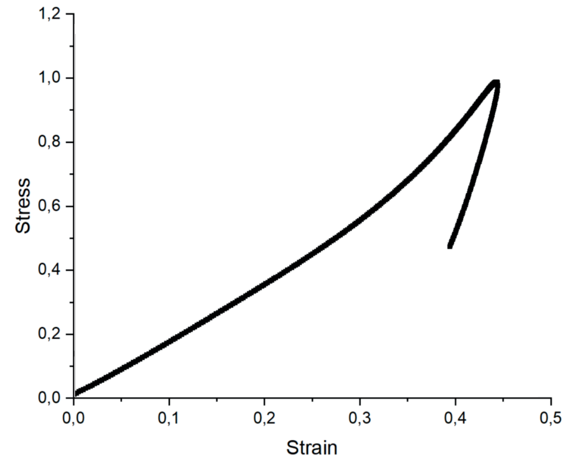
Área = 2421,4 mm^2

Energia de impacto: 20J

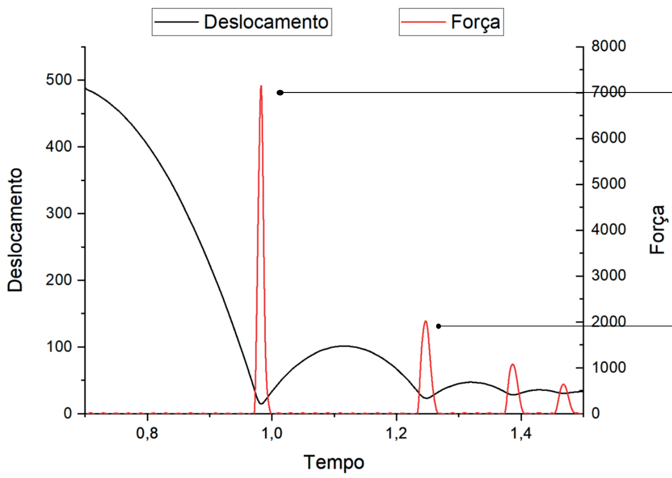


σ Máx = 1,05 MPa

ε Máx = 44.32 %



CORTIÇA 30MM (C30)



Massa total = 22 g

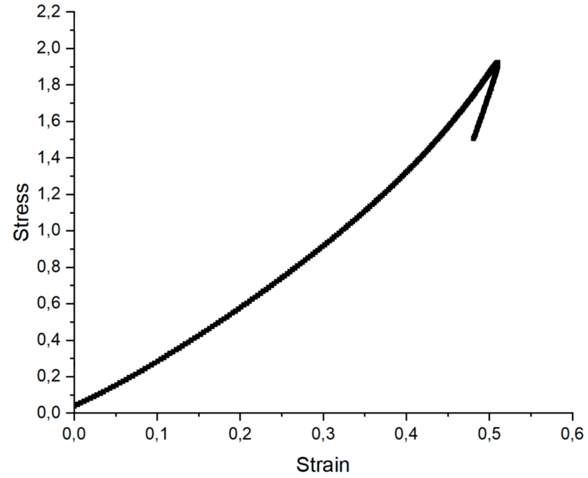
Espessura = 29,8 mm

Área = 3509 mm²

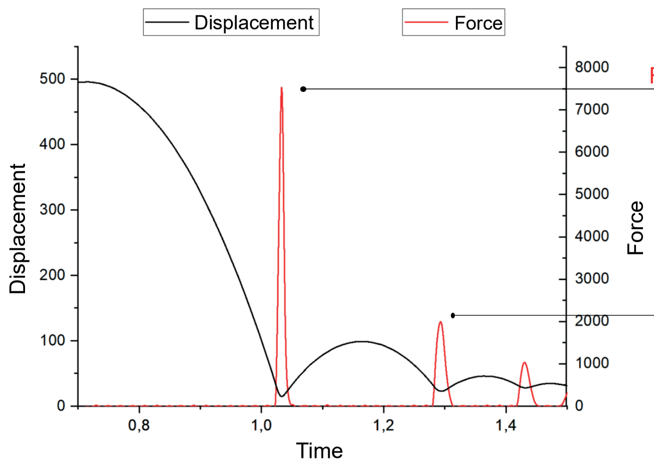
Energia de impacto: 100J

σ Máx = 2,03 MPa

ε Máx = 51.08 %



CORTIÇA 30MM + TPU (C30+TPU)



Massa total = 30 g

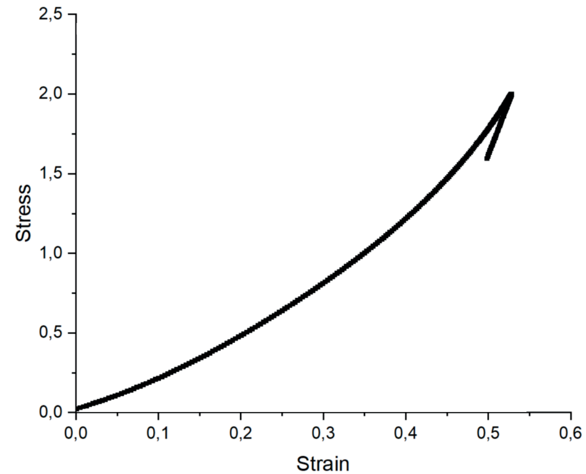
Espessura = 31 mm

Área = 3532 mm²

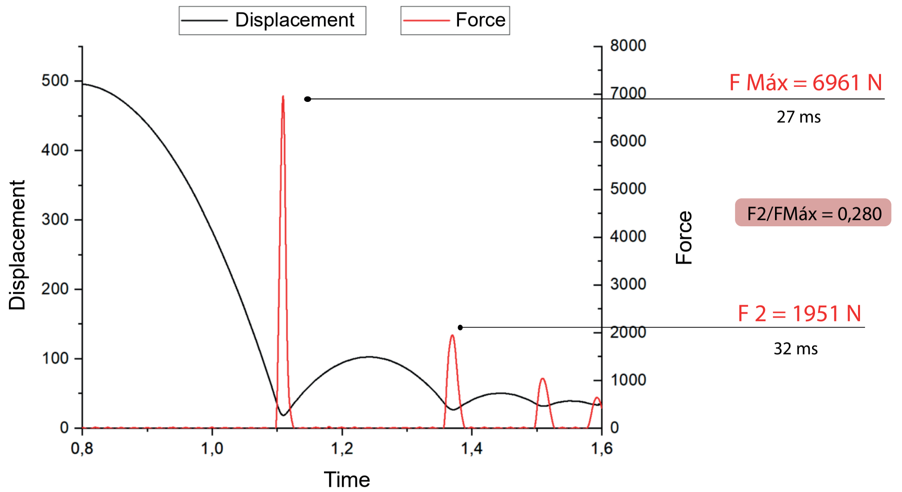
Energia de impacto: 100J

σ Máx = 2,13 MPa

ε Máx = 52.83 %



CORTIÇA 30MM + FLUIDO + TPU (C30-F-TPU [2])



Massa total = 41 g

Massa fluido = 10 g

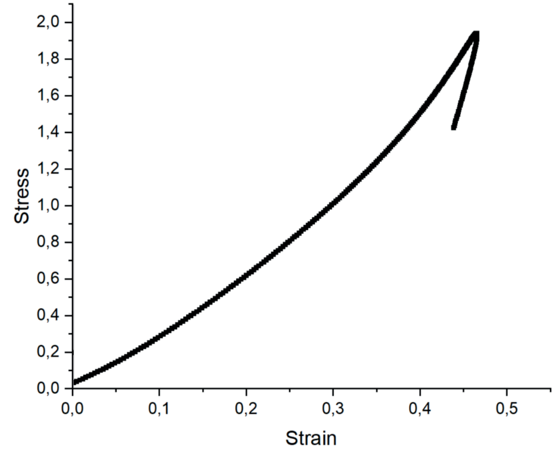
Espessura = 34,5 mm

Área = 3556 mm²

Energia de impacto: 100J

σ Máx = 1,95 MPa

ε Máx = 46.49 %

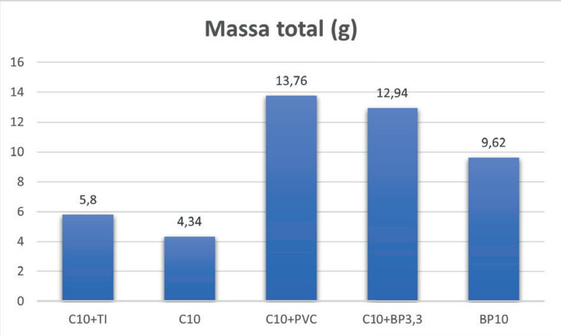


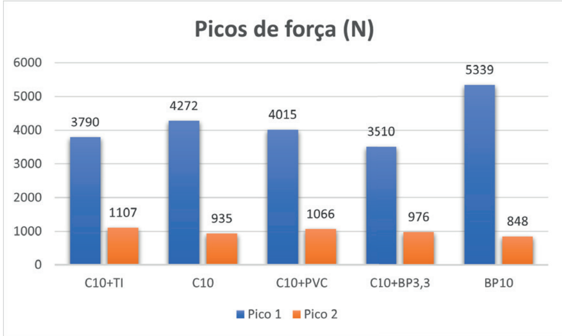
ENERGIA DE IMPACTO: **20 J**

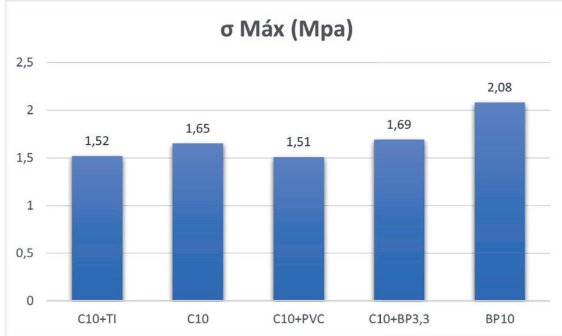
GRÁFICOS COMPARATIVOS

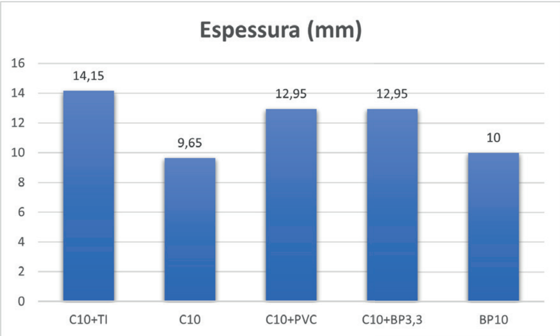
ENSAIO DE COMPRESSÃO

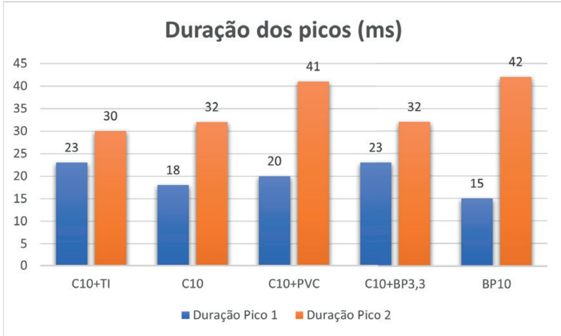
CORTIÇA DE 10MM ACOMPANHADOS DOS OUTROS MATERIAIS

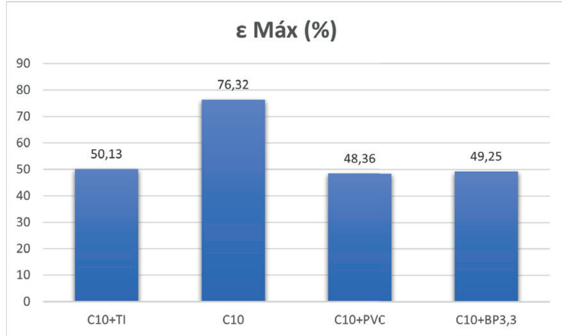


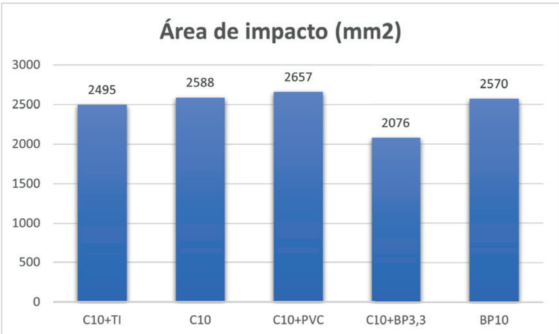


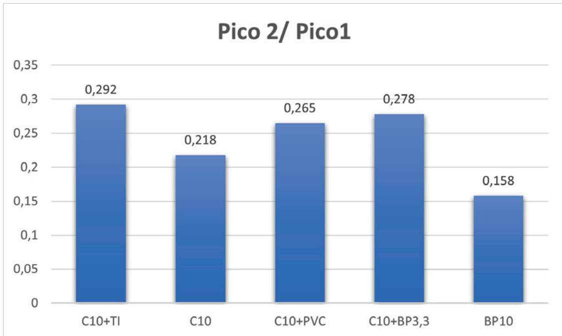


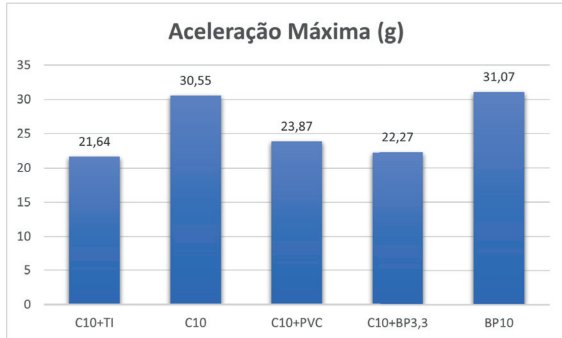












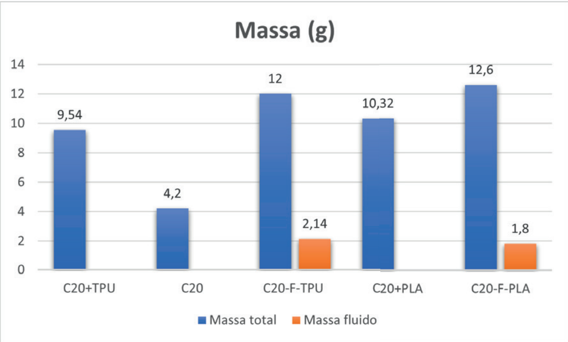
C10 = CORTIÇA 10mm TI = TECIDO IMPREGNADO PVC = PVC VERMELHO BP 3,3 = BORRACHA PRETA 3,3mm

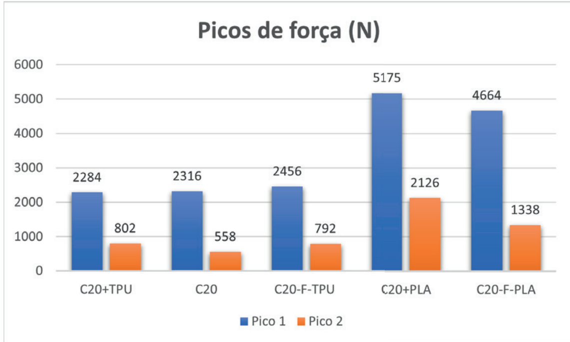
ENERGIA DE IMPACTO: **20 J**

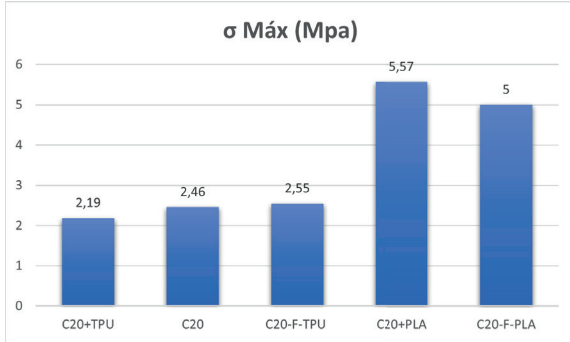
GRÁFICOS COMPARATIVOS

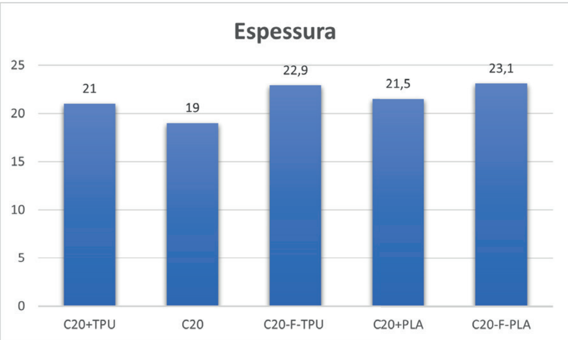
ENSAIO DE COMPRESSÃO

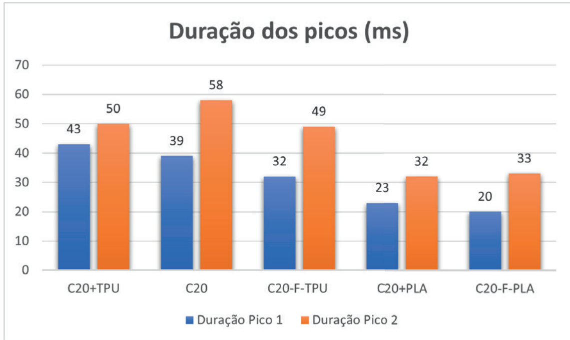
DESEMPENHO DO FLUIDO QUANDO ENCAPSULADO ENTRE CORTIÇA E TPU/PLA À 20 J

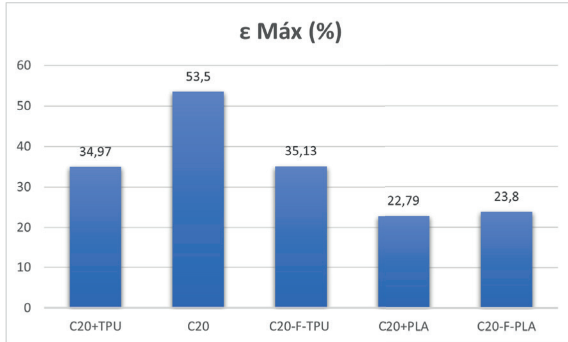


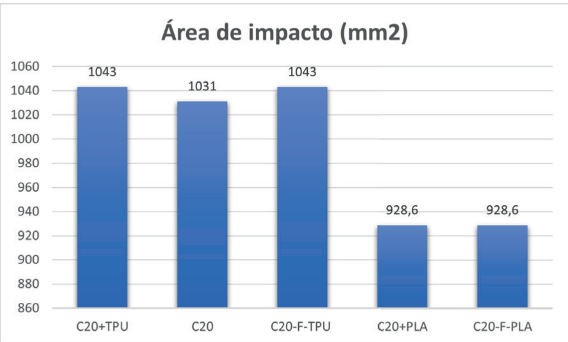


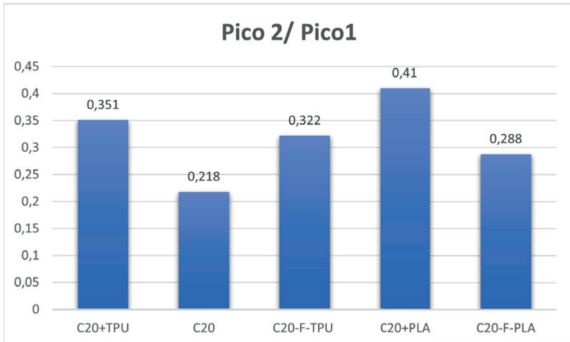


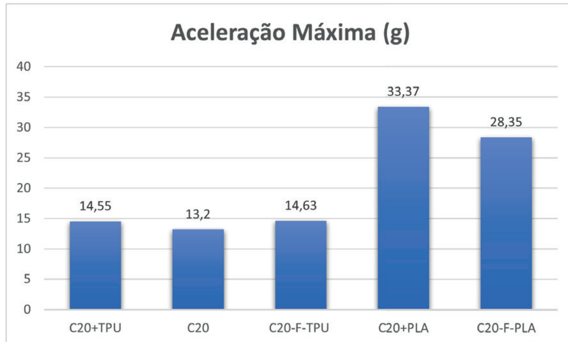












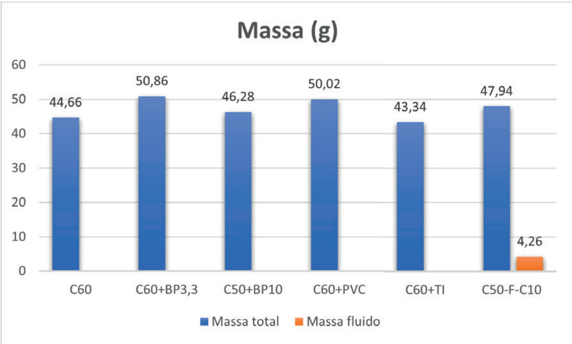
C20 = CORTIÇA 20mm   TPU = PEÇA EM POLIURETANO TERMOPLÁSTICO (TPU)   F = FLUIDO REOESPESSANTE   PLA = PEÇA EM ÁCIDO POLILÁTICO (PLA)

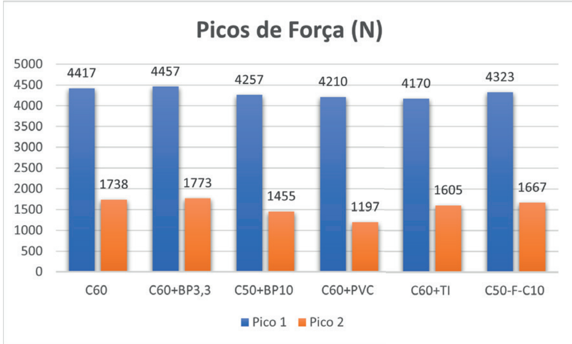
ENERGIA DE IMPACTO: **100 J**

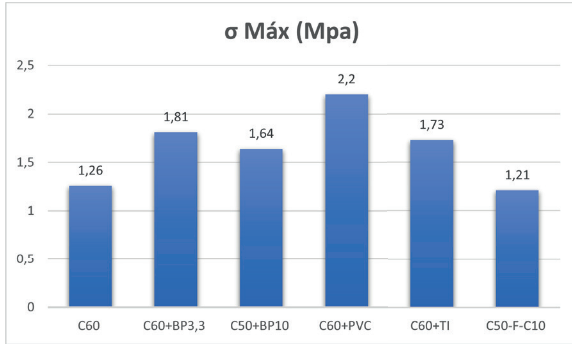
GRÁFICOS COMPARATIVOS

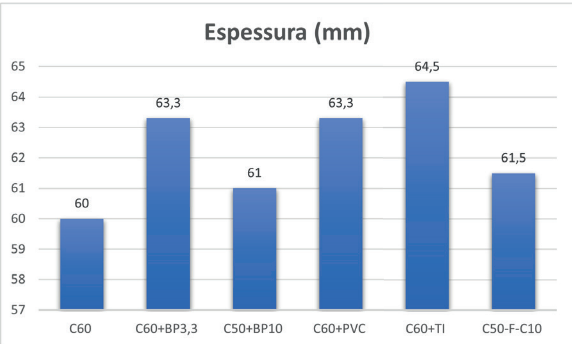
ENSAIO DE COMPRESSÃO

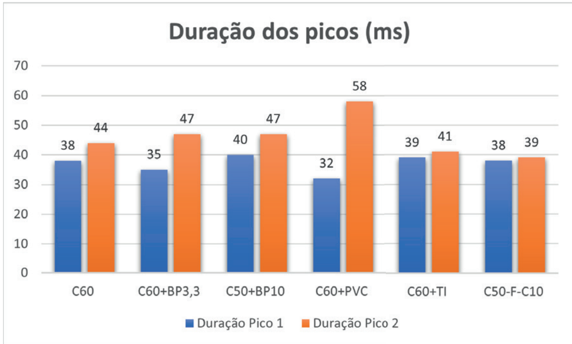
CORTIÇA DE 50 E 60MM ACOMPANHADOS DOS OUTROS MATERIAIS

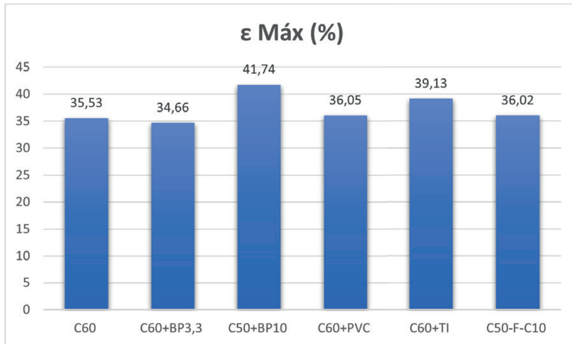


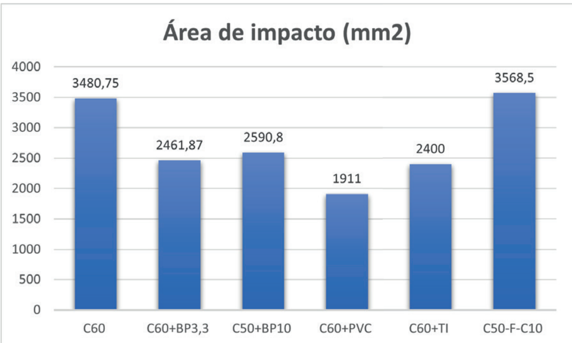


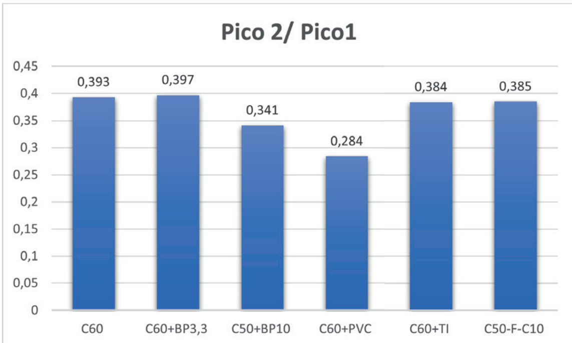


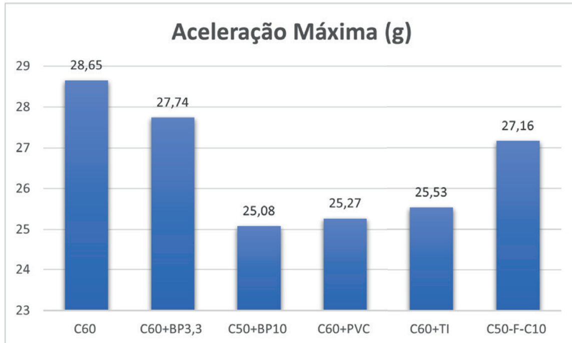












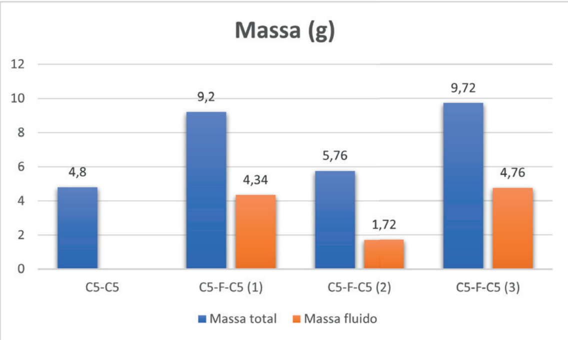
C60 = CORTIÇA 60mm   C50 = CORTIÇA 50mm   C10 = CORTIÇA 10mm   TI = TECIDO IMPREGNADO   F = FLUIDO REOESPESSANTE   BP 3,3 = BORRACHA PRETA 3,3mm   BP 10 = BORRACHA PRETA 10mm   PVC = PVC VERMELHO

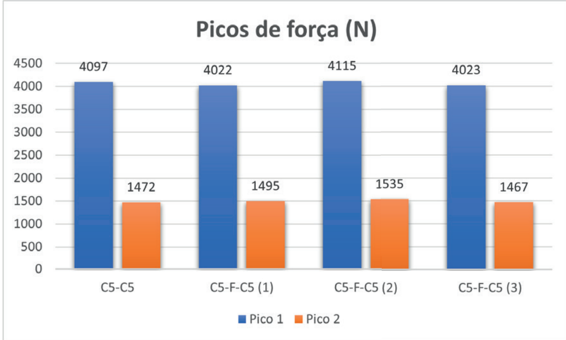
ENERGIA DE IMPACTO: **20 J**

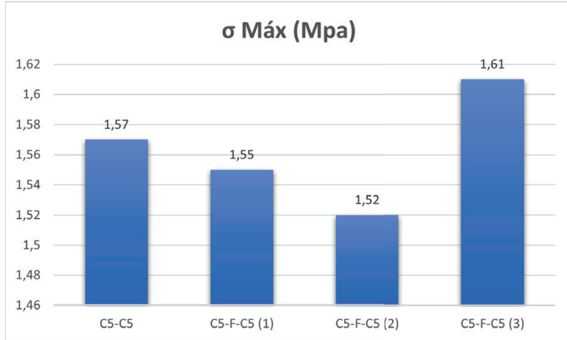
GRÁFICOS COMPARATIVOS

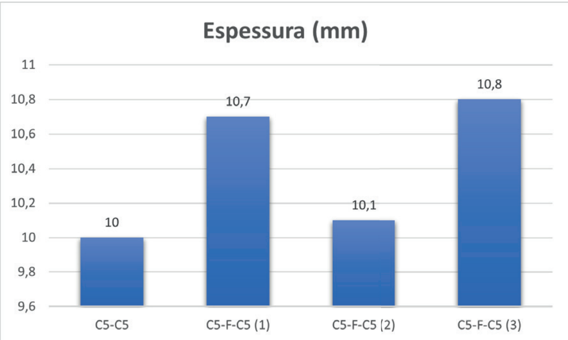
ENSAIO DE COMPRESSÃO

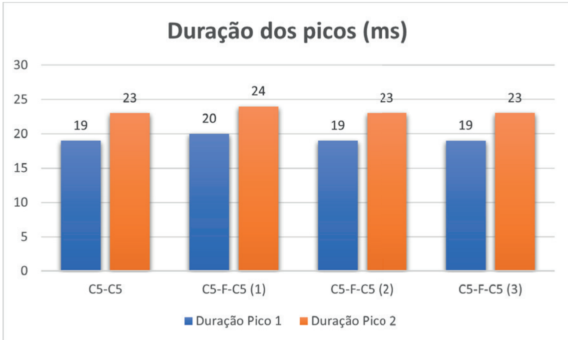
CORTIÇA 5MM SEM FLUIDO E 3 AMOSTRAS COM FLUIDO

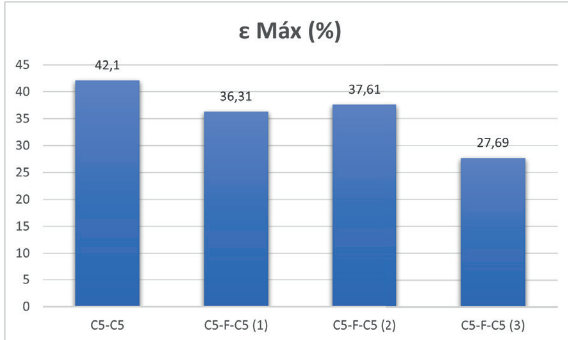


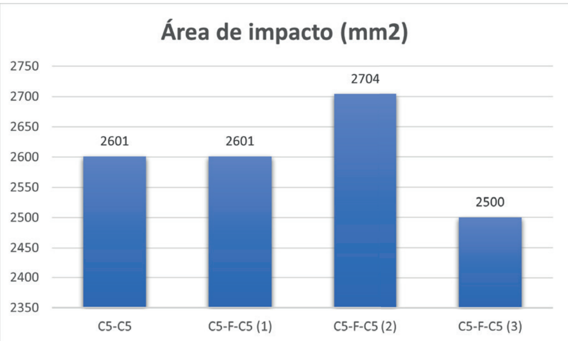


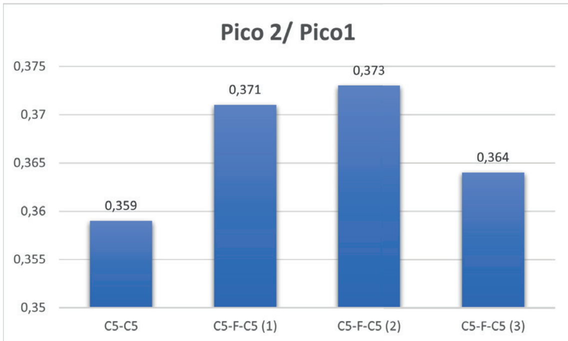


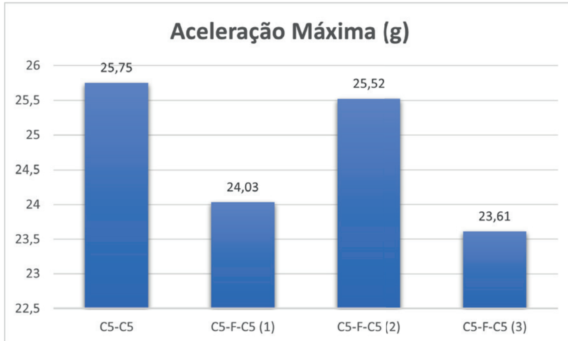












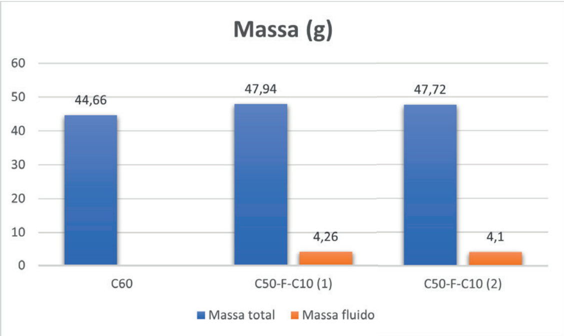
C5 = CORTIÇA 5mm F = FLUIDO REOESPESSANTE (1) (2) (3) = NÚMERO DA AMOSTRA

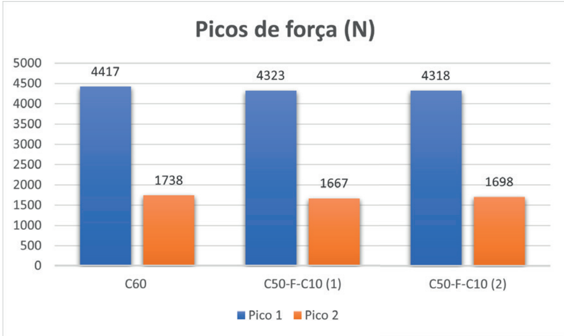
ENERGIA DE IMPACTO: **100 J**

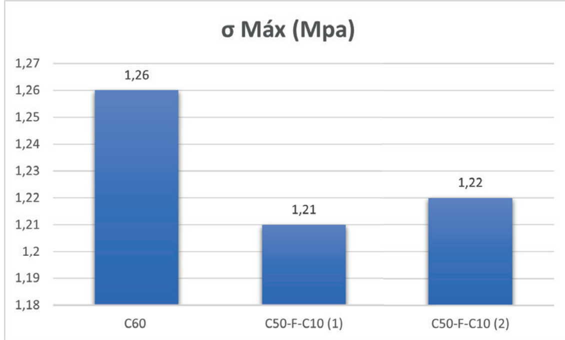
GRÁFICOS COMPARATIVOS

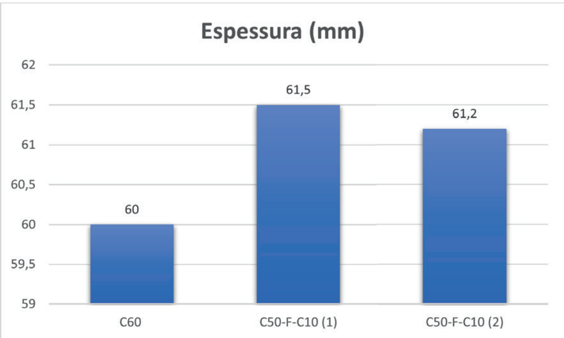
ENSAIO DE COMPRESSÃO

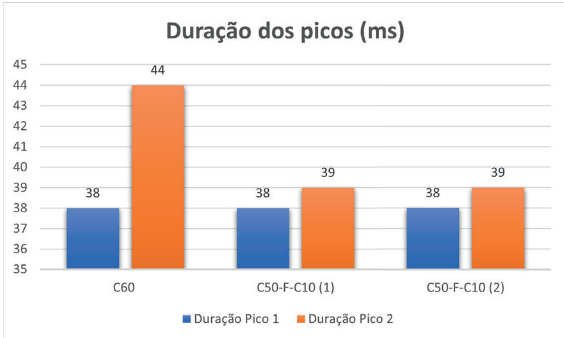
CORTIÇA 60MM SEM FLUIDO E 2 AMOSTRAS COM FLUIDO

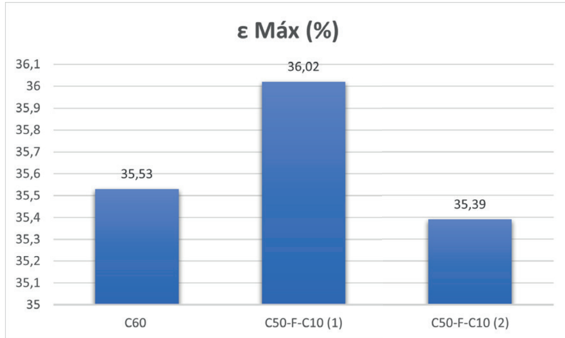


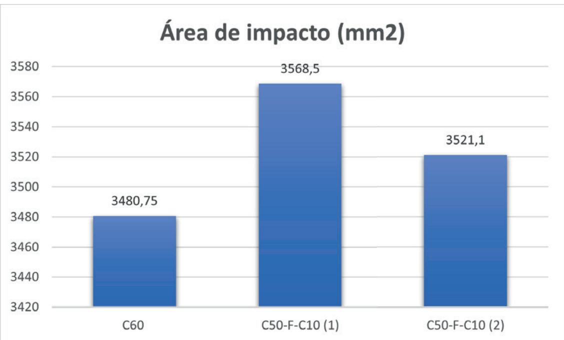


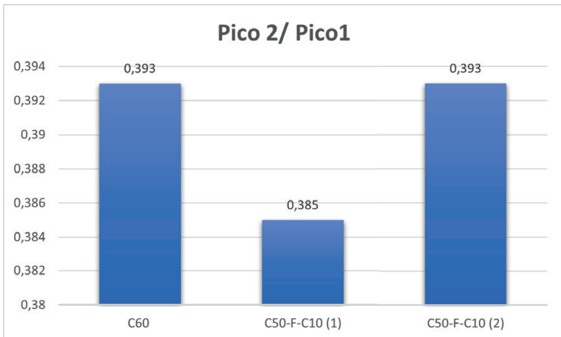


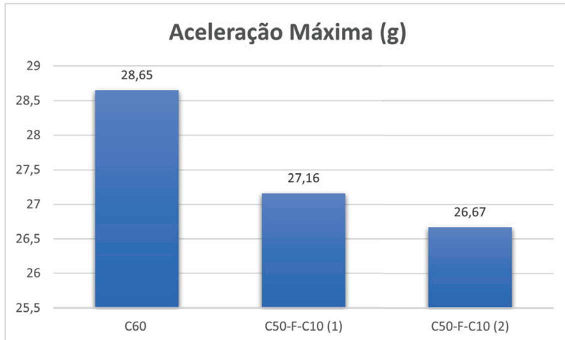












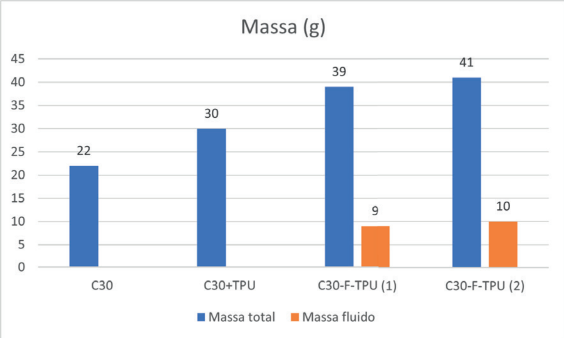
C60 = CORTIÇA 60mm   C50 = CORTIÇA 50mm   F = FLUIDO REOESPESSANTE   (1) (2) = NÚMERO DA AMOSTRA

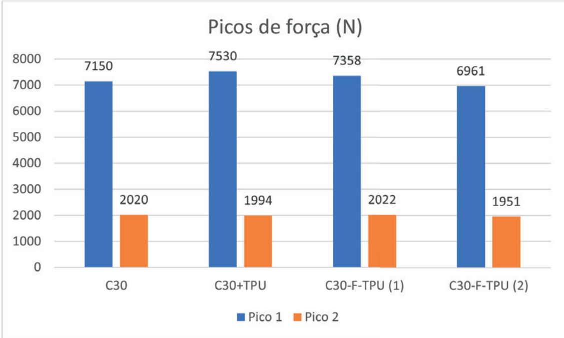
ENERGIA DE IMPACTO: **100 J**

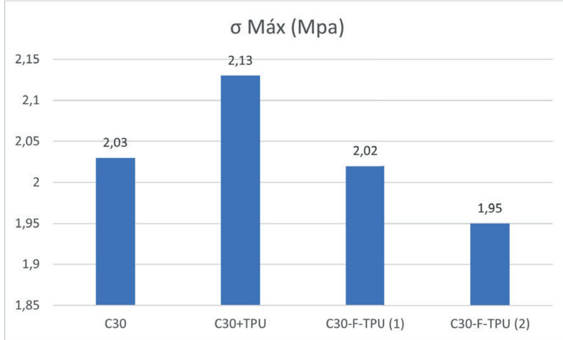
GRÁFICOS COMPARATIVOS

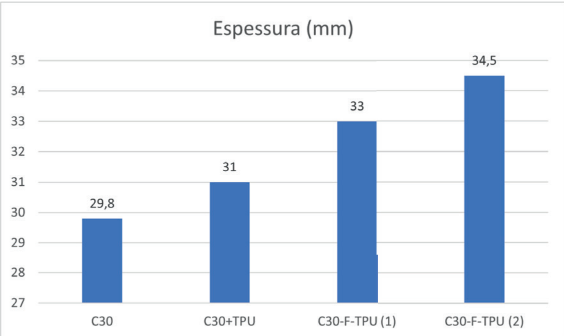
ENSAIO DE COMPRESSÃO

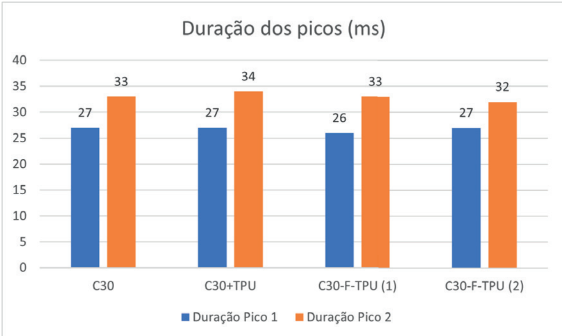
DESEMPENHO DO FLUIDO QUANDO ENCAPSULADO ENTRE CORTIÇA 30MM E TPU À 100 J

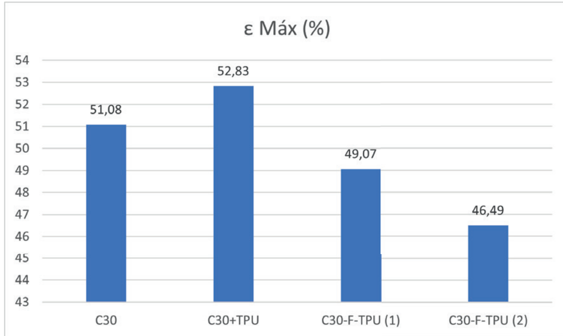


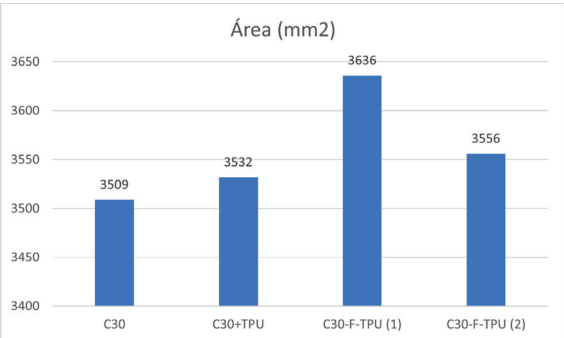


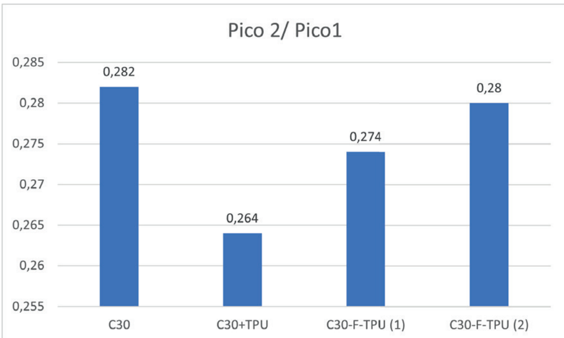


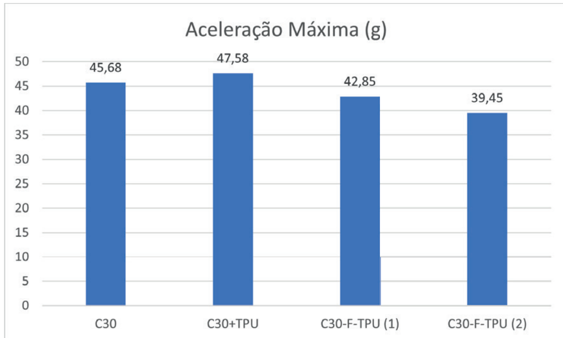




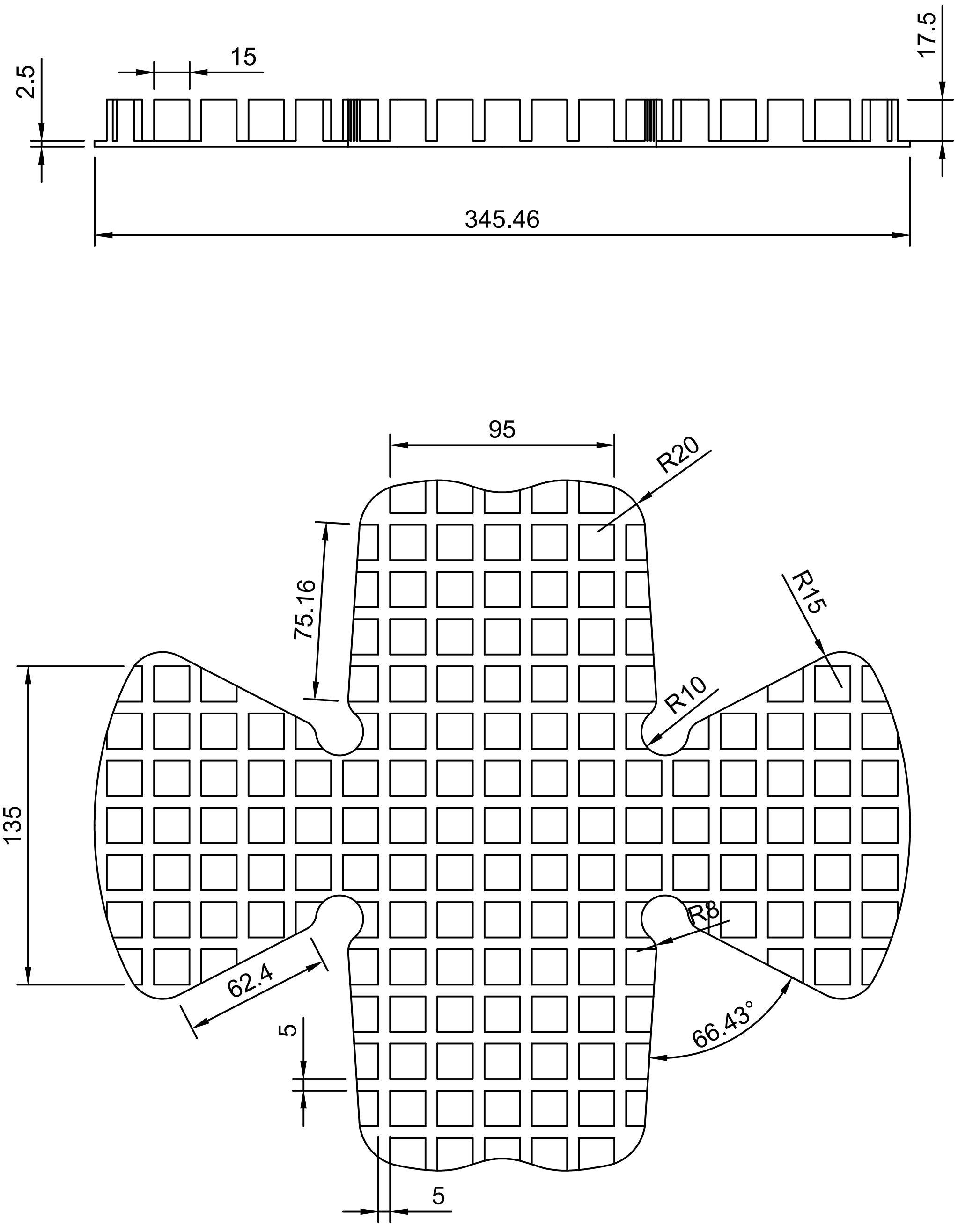


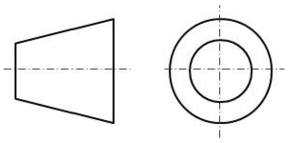


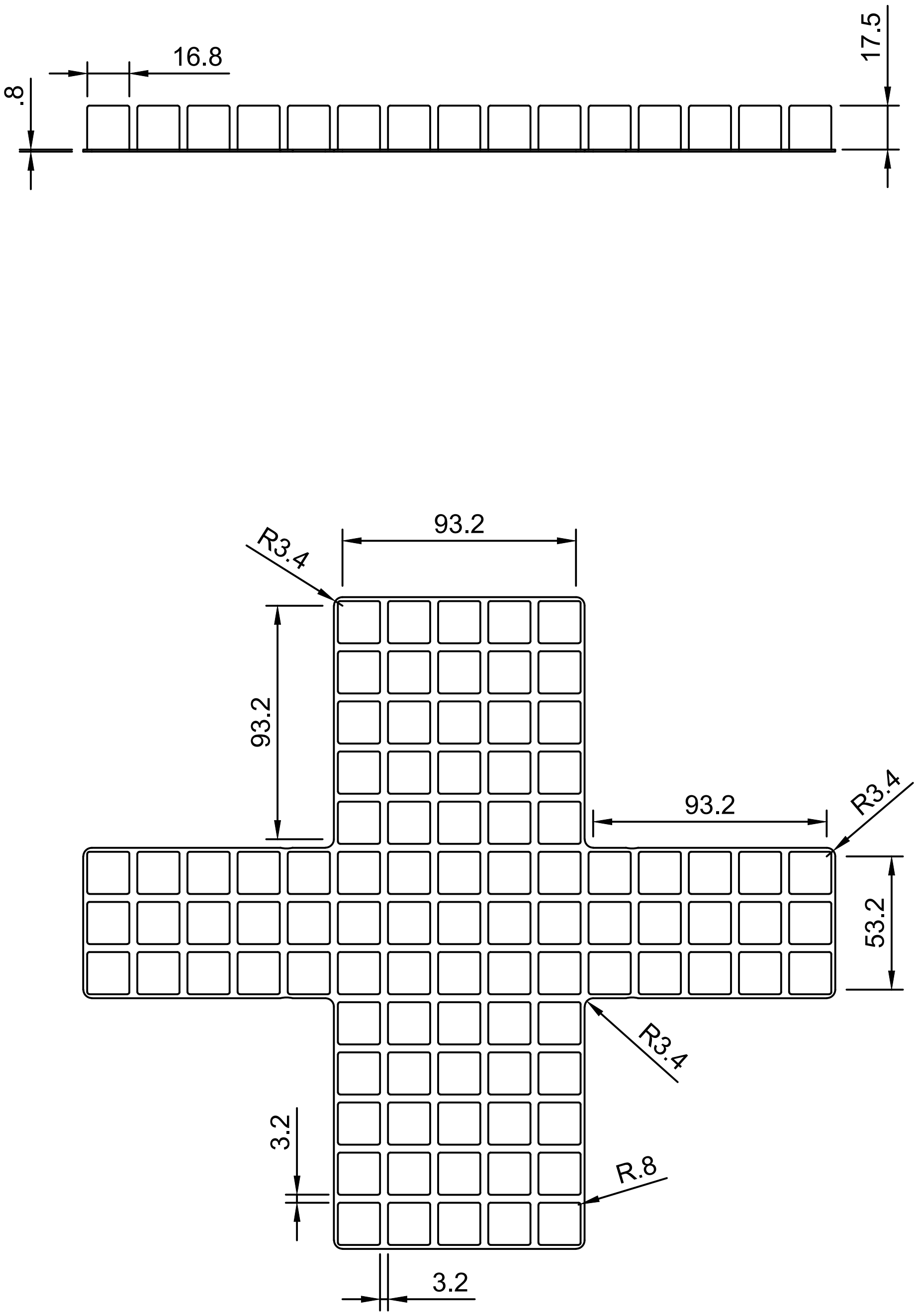




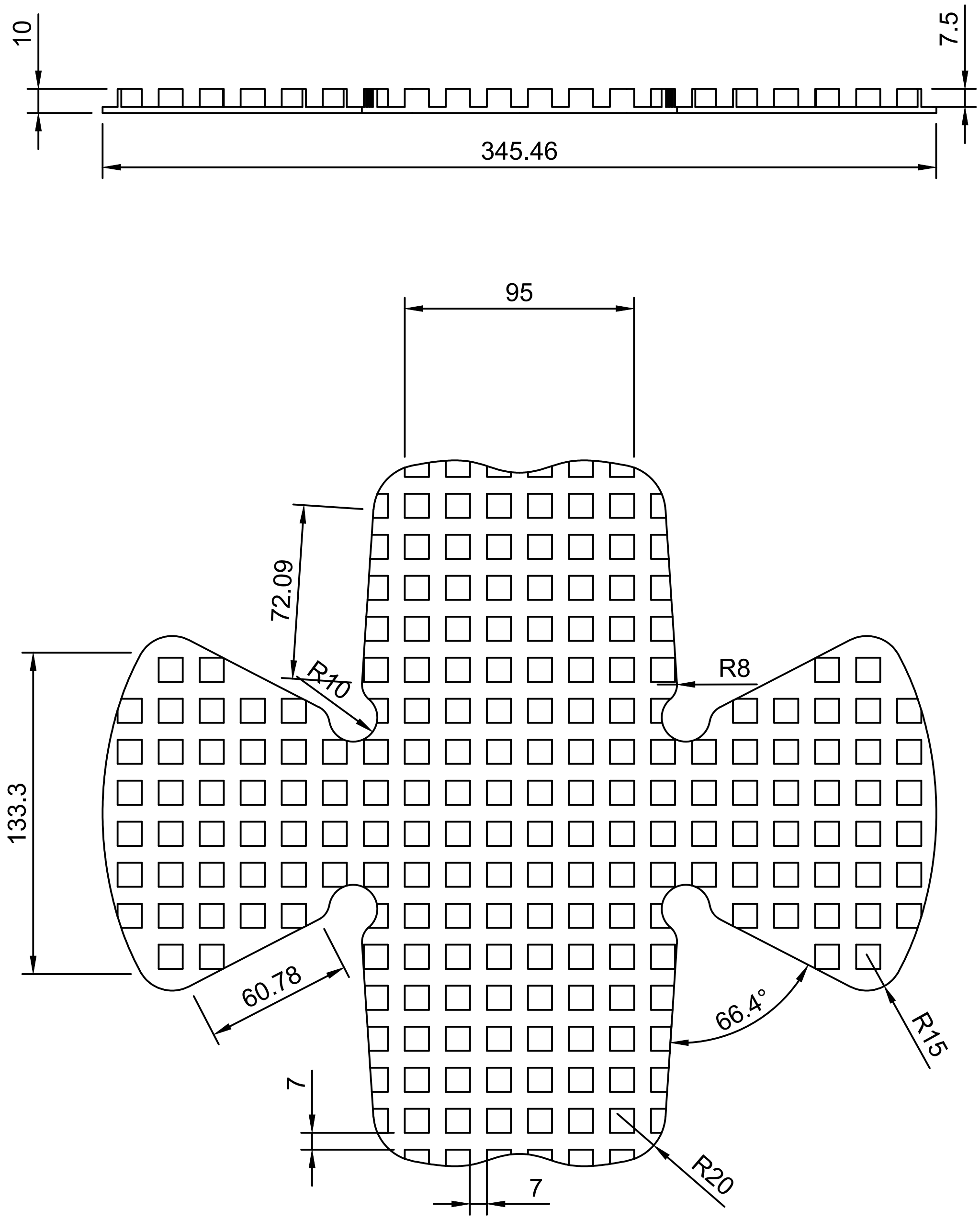
C30 = CORTIÇA 30mm TPU = PEÇA EM POLIURETANO TERMOPLÁSTICO (TPU) F = FLUIDO REOESPESSANTE (1) (2) = NÚMERO DA AMOSTRA



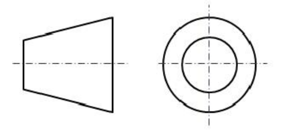
Disciplina Thesis	Autor Gabriel Serra	Material Cork
	Tipo Individual part	Unidades Milimeters
	Peça Cork 20mm	Escala 1:3
		Data 23/10/2021 — Folha 1/5



Disciplina Thesis	Autor Gabriel Serra	Material TPU
	Tipo Individual part	Unidades Milimeters
	Peça TPU outer layer	Escala 1:3
		Data 23/10/2021 — Folha 2/5



Disciplina	Autor	Material
Thesis	Gabriel Serra	Cork



Tipo
Inidividual part

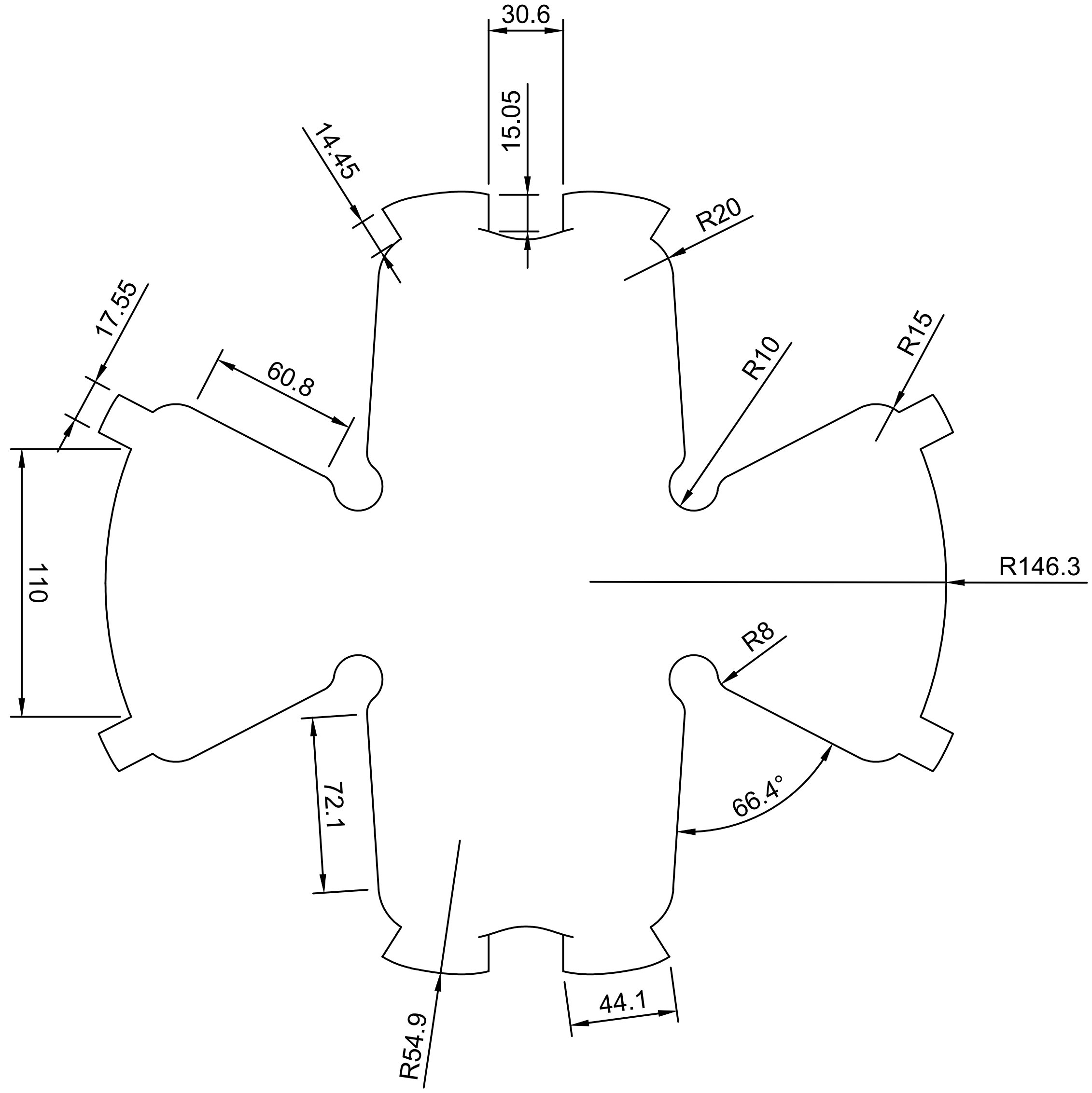
Unidades
Milimeters

Peça
Cork 10mm

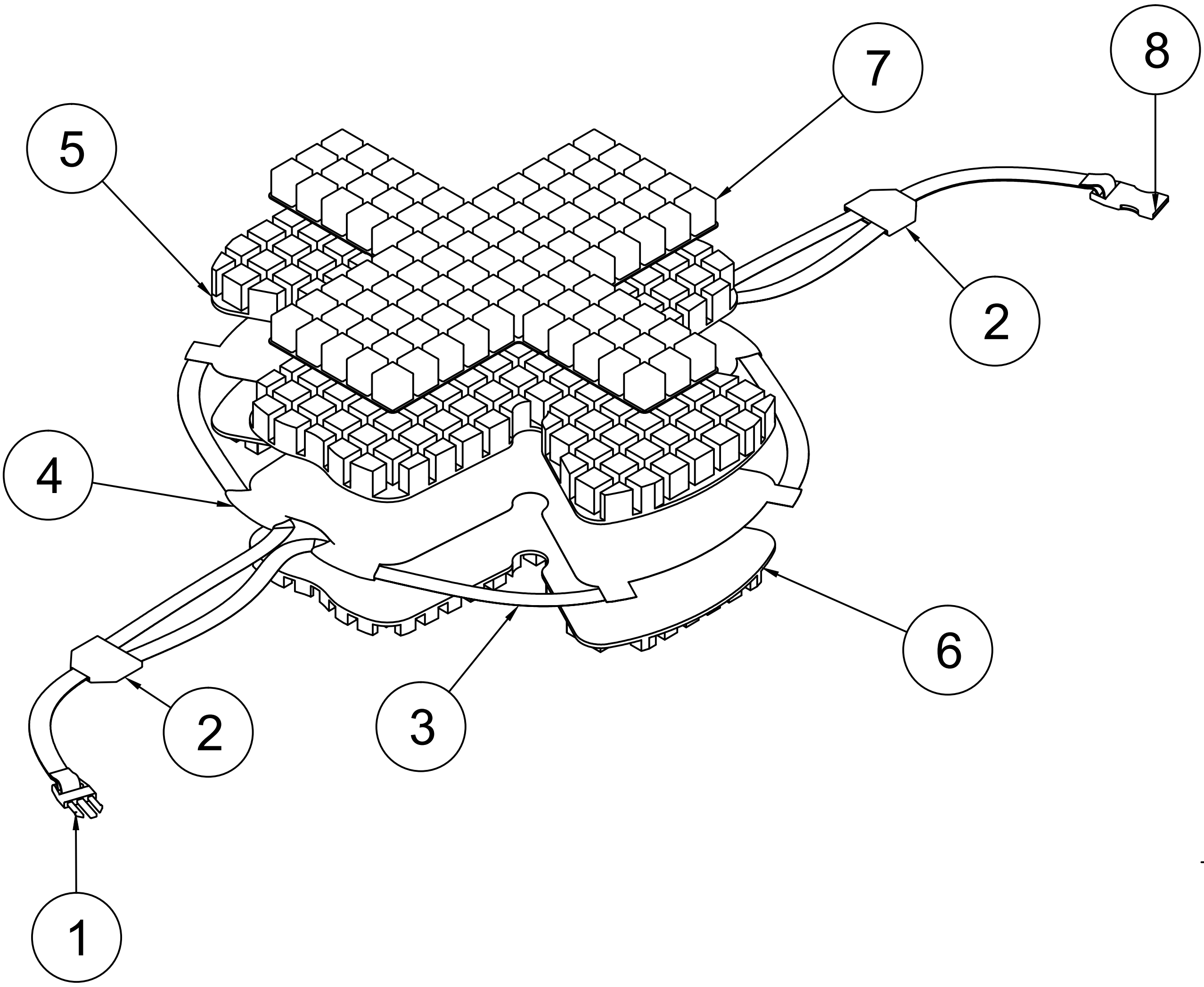
Escala
1:3

Data
23/10/2021

Folha
3/5



Disciplina Thesis	Autor Gabriel Serra	Material PET fabric
	Tipo Individual part	Unidades Milimeters
	Peça Fabric	Escala 1:3
		Data 23/10/2021 · Folha 4/5



Item number	Qty	Part name	Description	Material
8	1	Female buckle	To fix the helmet	PP
7	1	TPU outer layer	Acts as the "shell"	TPU
6	1	Cork 10 mm	Inner layer of cork	Cork agglomerate
5	1	Cork 20 mm	Outer layer of cork	Cork agglomerate
4	1	Interlayer fabric	Connecting agent between cork parts	PET fabric
3	1	Strap	For adjustment	Nylon
2	2	Adjustment part	To adjust the fit to the head	PP
1	1	Male Buckle	To fix the helmet	PP

Parts List

Disciplina	Autor	Material
Thesis	Gabriel Serra	Various
	Tipo: Exploded view/parts list	Unidades: Milimiters
	Peça: Complete helmet	Escala: 1:4
		Data: 23/10/2021 — Folha: 5/5