SULZER

White Paper

January 2024

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Poly (lactic acid) (PLA) foam is a biodegradable and sustainable material that has gained significant attention in recent years due to its mechanical and thermal properties and the high degree of flexibility from the three stereo-isomers L-, D- and Meso-Lactide that the polymer chain comprises of. Furthermore, regulations in many industrialized countries are now favoring biodegradable materials over single-use plastics. PLA foam has the potential to be used in various fields, including cushioning packaging, heat insulation, noise reduction, and even filtration and adsorption. It is crucial to understand PLA properties and its foaming behavior to understand its potential applications and to optimize its production process. In this article, we aim to provide a comprehensive review of the whole spectrum of PLA foam applications.

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Overcoming the small foaming window

The application and development of PLA-based foams were for a long time limited due to the low melt strength, poor thermal resistance, slow speed of crystallization, and the brittleness of PLA raw material [1]. This has significantly limited the commercial exploitation of PLA-based foams for a long time. To overcome this issue, chain extension, and blending have been explored as strategies to improve the foamability of PLA.

Chain extension involves the use of chain extenders, which are molecules that can react with the polymer chains to increase their length and induce branching or cross-linking. This can lead to an increase in the melt strength of the polymer, making it more suitable for foaming. For example, the addition of dicumyl peroxide as a chain extender has been shown to improve the foamability of PLA, resulting in a higher expansion ratio or smaller cell sizes. Another example is multifunctional epoxy-based chain extenders that result in an improvement in the foam morphology, including smaller cell sizes or lower densities.

Blending is another approach that has been explored to improve the foamability of PLA. This involves the mixing of PLA with other polymers to alter its properties and make it more suitable for foaming. For example, the addition of starch to PLA has been shown to improve its foamability, resulting in a higher expansion ratio and smaller cell sizes. This is because starch – unlike PLA – becomes more viscous with increasing temperature, which can help to improve the foamability of the blend [14],[8].

Properties and applications of PLA Foam

Packaging applications

The largest application for polymers and foamed polymers is packaging [2]. For PLA as a biodegradable polymer within an industrial composting environment, food packaging seems the most natural fit. Indeed, PLA can be blended with FDA-approved additives, such that it can be used for food applications. These include tray inserts for fresh meat or seafood, cup sleeves for the fast-food industry, but also egg cartons, and insulated packaging for hot and cold drinks. However, also non-food applications have been successfully commercialized, such as electronic device packaging, medical equipment, and industrial parts packaging. Even the automotive industry uses component packaging for headlights and sensors. This shows the strong commitment of those companies to reduce plastic waste.

One way to produce PLA foam is by extrusion: PLA pellets are mixed with additives and fed into a co-rotating extruder. Once the polymer is molten, the blowing agent, typically supercritical CO_2, is added and thoroughly mixed with the PLA. The blend is subsequently cooled down in a melt cooler and pressed through a die. The die gives the final shape of the foam, i.e., usually flexible sheets or boards. The sheets will typically have a thickness between 0.5 and 1.0mm, densities as low as 150 g/l, and high closed-cell content. These are the typical dimensions and properties used for thermoformed food packaging, which means that PLA can be used as a drop-in polymer in existing thermoforming infrastructure. Sulzer has the capability to design such foam lines.

Another method to manufacture PLA foam packaging is to produce beads that will be molded into the exact shape of the transported goods. The beads are also produced by an extrusion-based process, with the main difference being that the die is in contact with an underwater pelletizer system. The pelletizer will produce a foam particle size of 3-4mm typically. The particle will then be directly used in a steam chest molding device, where a final density of 30-75 g/l can be achieved. Both density and mechanical properties are comparable to existing EPS products.

Such PLA foam packaging is already produced commercially. One example is Bewi, that produces PLA BioFoam® for protective packaging solutions [3]. Also, Ricoh claims to be the first mover in PLA foam production of sheets [4]; Eco-Products [5] and World Centric [6] have a vast range of PLA foamed and non-foamed food packaging products.

Another early adopter of PLA foam products is BASF. Within its Ecovio product line BASF has added Ecovio EA, a PLA particle foam with high impact resistance designed for transport packaging for high-value or delicate goods [7]. Like EPS, according to BASF, the PLA foam has a very good energy absorption and good resilience, even when subjected to multiple impact loads. Ecovio is based on a proprietary blend of PBAT and PLA, and has been foamed with pentane to a density of 700 g/l. The particle size of the beads is 1.05mm. After the pre-expansion the beads will have a bulk density as low as 25 g/l.

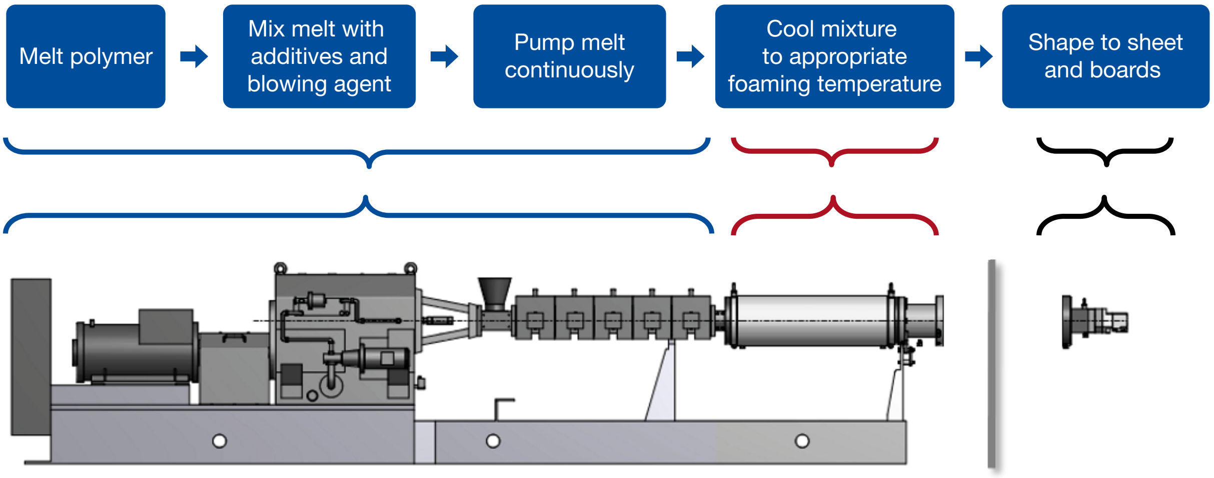
Thermal insulation applications: Wall insulation

Another application that requires good thermal insulation properties is wall insulation in the construction industry [9]. This application has for a long time been dominated by EPS due to its good insulation properties, good chemical stability, and low costs. On the downside, it is based on fossil raw materials and has a bad reputation as for its end-of-life options. This is where PLA foam contribute, with its bio-based origin and biodegradability. But how about the thermal properties? In a blend with 40 wt.-% PCL and rice straw PLA foam showed an excellent low heat conductivity of 0.038 – 0.040 W/mK, which is comparable (yet not identical!) to typical values for EPS. Rice straw is a cheap biomaterial, which reduces the overall cost of the wall insulation and acts as a nucleating agent during the foaming process. PCL is a biodegradable polyester material and has the advantage of excellent toughness and biodegradability.

Also, the low heat conductivity of PLA foam has been used for cold containers of all kinds, ranging from vaccines to ice-cream. For example, Corbion and Synbra showcased a PLA foam-based ice-cream packaging in 2015.

Finally, a research team from the University of Canterbury, Christchurch, New Zealand has shown that plastic cutlery with a composite of PLA and talc can be recycled to a PLA foam that can be used for thermal insulation purposes, however this approach has not yet been commercialized [11].

Figure 1: Polymer Foam Line (Picture courtesy from Sulzer)



Acoustic insulation

In the publication of Yao et al. [18] it was possible to see how comparing the single-layer foam to the multilayered structure showed improved mechanical and sound insulation properties Such acoustic panels can be used in public buildings, theatres and movies and are a sustainable solution for an existing market.

Oil filtration and adsorption

Existing methods for oil absorption typically rely on chemicals that are fossil-based, e.g. polypropylene fiber, polyurethane or the proprietary chemical “Corexit”, which is mainly made of hydrotreated light petroleum distillates, propylene glycol, and an organic sulfonate as the active ingredient. All these absorbents and dispersants are non-biodegradable and cannot be re-used. Rather they need to be disposed in accordance with environmental regulations. Other methods include using porous materials, such as nanowire membranes, activated carbon, zeolites, carbon nanotubes, or graphene. However, most of the existing materials have drawbacks such as high costs, complicated fabrication procedures, or difficulties to disposal. More importantly, the absorbents are generally chemically stable and non-biodegradable, which may cause new environmental problems in case of mishandling. There is therefore a high demand for eco-friendly, low-cost, and high-absorbing sorbents. [13], [14], [15]

Bio-based and biodegradable poly (lactic acid) (PLA) foams present an innovative solution. PLA foam is relatively inexpensive to produce, it can be used multiple times and it has a very high adsorption capacity of up to 30 g oil / g PLA foam. So far, the PLA foam for oil absorption purposes has been produced in an autoclave for scientific purposes, however for industrial purposes extrusion-based PLA foam is the more cost-efficient approach. Typically, the production of extrusion-based polymer foams consume less water, space and it is a continuous process.

Shock impact protection

PLA foam has also been widely studied for its impact absorption properties. The impact absorption properties of PLA foam are influenced by several factors, including the foam density, cell structure, and mechanical properties of the material. The density of PLA foam plays a role in its impact absorption properties. Higher-density foams tend to have better impact absorption capabilities as they offer more resistance to deformation. However, it is important to find the right balance between density and flexibility to ensure optimal impact absorption. The mechanical properties of the PLA matrix can be optimized for impact absorption by blending the PLA with impact modifiers, such as elastomers, core-shell impact modifiers, reactive toughening agents, or nanoparticles. This will then finetune the properties of the PLA foam. [17]

These properties make it a suitable material for applications where impact protection is required, such as in packaging, sports equipment, and protective gear. As for commercially available products, it seems that the bike helmet market is still dominated by EPS foam, inserted into a polycarbonate or ABS shell. However, first products with PLA foam as cushioning material for (moto-)cyclists are available [16].

Conclusion

PLA foam, a sustainable and versatile material, has found diverse applications. Overcoming initial limitations through chain extension and blending has made it a biodegradable alternative in various fields.

PLA foam excels in food packaging, with companies like Bewi, Ricoh, and BASF offering innovative solutions.

In acoustic insulation, PLA foam stands out, offering eco-friendly solutions for public buildings and theaters. Additionally, its oil adsorption capacity addresses the need for sustainable sorbents in environmental cleanup.

PLA foam's impact absorption properties make it suitable for protective gear and sports equipment. Its versatility and biodegradability make it a promising material across industries, offering sustainable solutions to contemporary challenges. Continued research and innovation will likely expand its role further.

As research and innovation continue to advance this PLA foam, we can anticipate a sustained and increasing demand, making it a driving force in shaping a greener, more sustainable future for industries across the board.

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