Chapter 9
The Recycling of Construction Foams: An Overview

Nuno Gama, Ana Barros-Timmons, and Artur Ferreira

Abstract In 1987, the United Nations Brundtland Commission defined sustainability as "meeting the needs of the present without compromising the ability of future generations to meet their own needs." Yet, after all these years, the humankind is dealing with catastrophic environmental problems which may jeopardize the future generations wellbeing. One cause of such issue is pollution associated to polymer's disposal. Polymers are mainly produced using petroleum derivatives and/or non-degradable. In addition, after their use, they are normally disposed in land fields or burned for energy. Yet, due to environmental problems, these solutions are not valid options, so plastic wastes must be recycled and used to produce new materials. This circular economy concept is not only a requirement for preventing pollution but is also a need for the reduction of the costs associated with their production and for the enhancement of the eco-efficiency of materials. Furthermore, this approach also addresses the risk of shortage of raw materials in the medium future. With this in mind, this document intends to give an overview of the recycling of construction foams with special focus on polyurethane (PU) and polystyrene (PS) foams. It aims to highlight the possible routes to recycle construction foams, presenting the differences and challenges of recycling different types of polymers. In that perspective, chemical and mechanical recycling routes are discussed, as well as energy recover alternatives. Finally, life cycle analysis (LCA) reports of these products are presented.

Keywords Circular economy · Building's circularity · Sustainability · Polyurethane foam · Expanded polystyrene

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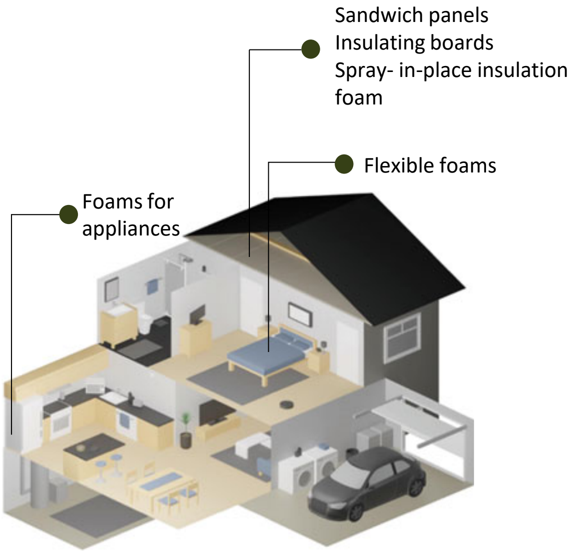
9.1 Polymer Foams

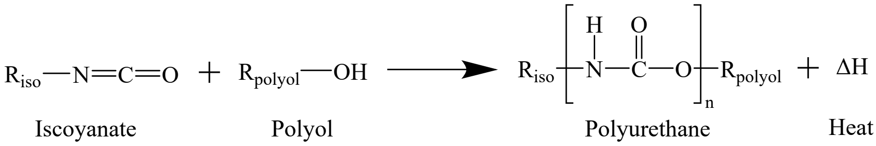
Polymer foams are porous structures, therefore extremely lightweight. Furthermore, they are versatile, since their mechanical properties can be adjusted, are highly durable, and have excellent sound absorption and thermal insulation properties, among others [1]. All these characteristics, together with their low cost, make them the primary choice to be used in protective packaging, thermal and sound insulation, or seat cushioning applications. Hence, they are indispensable i.e. for the construction industry, automotive or packaging sectors [1].

Theoretically, all polymers can be foamed, in addition, different process of foaming can be used. Extruded foams based on polystyrene (PS), poly(vinyl chloride) (PVC), polyethylene (PE), polypropylene (PP) or poly(ethylene terephthalate) (PET) are used in food, construction, decoration, packaging, medical application; injected foams-based PS, PP or PE are used in automotive, mounded beads based on PS or PP are used in food and packaging sectors, among many others. This results in materials with different properties and different applications, as already mentioned [2].

Due to the wide variety of applications, the global market of polymer foams was valued at USD 123.1 billion in 2021 and is expected to expand at a compound annual growth rate (CAGR) of 3.6% from 2022 to 2030 [3]. In what concerns the foams used in construction, they are mainly produced from PU or PS (representing almost 50% of the market [3]), but phenolic resins and PVC foams can be used as well. Independent of the type of polymer, they can be classified as flexible which are mainly used for dumping and sound absorption, or classified as rigid which are mainly used as structural or thermal insulation materials, as presented in Fig. 9.1.

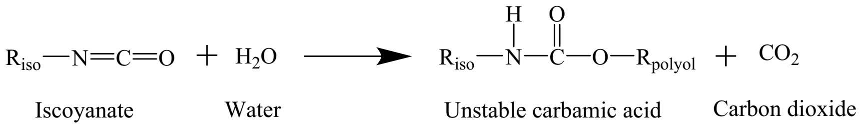
Fig. 9.1 Types of foams used in construction (Adapted from Metgen [4])





$$R_{iso}-N=C=O + R_{polyol}-OH \longrightarrow R_{iso}\left[-\overset{H}{N}-\overset{O}{\overset{\|}{C}}-O-\right]_n R_{polyol} + \Delta H$$

Scheme 9.1 Reaction scheme of polyurethane production [7]



$$R_{iso}-N=C=O + H_2O \longrightarrow R_{iso}-\overset{H}{N}-\overset{O}{\overset{\|}{C}}-O-R_{polyol} + CO_2$$

Scheme 9.2 Reaction scheme of the isocyanate with water [7]

9.1.1 Polyurethane Foams

PU foams correspond to 50% of global PU consumption, being mainly classified as flexible foams or rigid foams. They are the main type of foam used in construction, since they can be used to produce thermal insulation boards, sandwich panels, spray in-place foam, structure panels, pillows, mattress, etc. as illustrated in Fig. 9.1 [5].

All of these types of foams follow similar chemistry, being synthetized by the reaction between the OH (hydroxyl) groups of a polyol with the NCO (isocyanate functional groups) of an isocyanate, as illustrated in Scheme 9.1 [6].

Where R_{iso} and R_{polyol} are isocyanate and polyol moieties, respectively. Normally, the polyol has an average functionally ~3 and the isocyanate have an average ~2, therefore, the ensuing polymer is highly crosslinked. This means that PU foams are thermoset polymers.

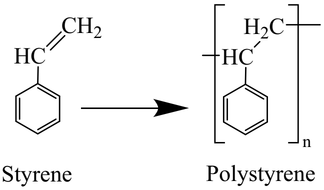
Besides the polymer reaction, the cellular structure of PU foams results from a parallel reaction between the isocyanate groups and water which releases CO_2 as presented in Scheme 9.2, which is trapped within the cells.

The PU foams expanded using water as blowing agent do not present thermal conductivity suitable for thermal insulation applications, hence, these type of materials requires the use of physical blowing agents (such as solvents with low boiling point such as *n*-pentane, acetone, or hexane) which expand the polymer by vaporization, are frequently used [8].

9.1.2 Expanded Polystyrene

Expanded PS (EPS) is ideal to be used as lightweight filler, damping and insulation materials, hence, it is mainly used in building applications to insulate wall structures (in the cavity, internally or externally), roofs and floors [9].

Scheme 9.3 Polymerization reaction of styrene



It is a thermoplastic polymer based on the styrene monomer (as presented in Scheme 9.3) and to produce EPS products, the PS resin is blended with 4–7% (by weight) of a hydrocarbon blowing agent (usually *n*-pentane) to form an expandable PS commonly referred in the industry as ‘bead’. Next, the beads are expanded to about 40 times their original size using a flow of steam. This causes the blowing agent to boil and a honeycomb of closed cells is formed. In this form EPS, consists up to 98% of gas [9].

Similarly, boards of extruded PS (XPS) are commonly used in construction, which are manufactured using extrusion. These materials presents a closed-cell structure which provides low thermal conductivity, prevents the penetration of water and ensure strength and durability [10].

9.2 Recycling of Polymer Foams

As mentioned, polymer foams are mainly produced using petroleum derivatives. In addition, not all polymers can be easily reprocessed therefore, after their use they are normally disposed in land fields or burned for energy [11, 12]. As a consequence, the pollution associated with polymers has become one of the most important environmental issues, since the disposal of these products overwhelms the world’s ability to deal with them.

Following this issue, the European Community is implementing measures for the prevention of the disposal of plastic urban residues, following the circular economy principles [13].

Hence, the European Union has become a pioneer against plastic pollution. In fact, the Directive 2019/904 of the European Parliament which aims to reduce the volume and impact of single-use plastics products on the environment is a major example of the measures being taken [14].

There are two major methods for recycling polymers: mechanical recycling and chemical recycling. The type of the recycling process to adopt is dependent on the type of polymer since thermoset and thermoplastics behave differently when exposed to heat. While thermoplastics melt under heat, thermoset can degrade at elevated temperatures [9]. In Fig. 9.2, the schematic representation of mechanical and chemical recycling of foam wastes, to produce recycled foams is represented.

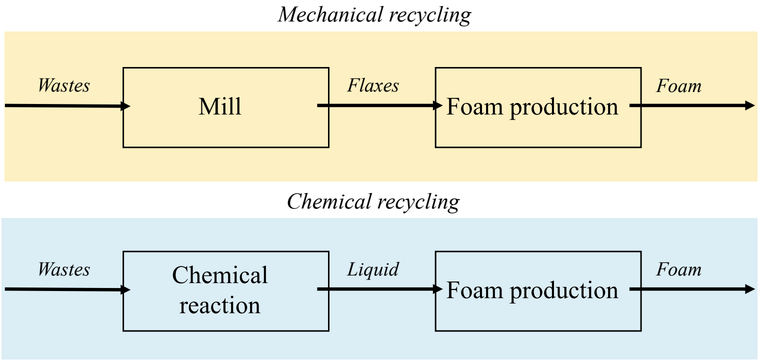


Fig. 9.2 Schematic of mechanical and chemical recycling

In mechanical recycling, polymer scraps are milled and reintroduced in the production process, while the chemical recycling follows the degradation principle. In this case, the polymer wastes are depolymerized via a chemical reaction into oligomers, which can be used as raw-materials to produce new polymers [15]. Nonetheless, it must be highlighted that the life cycle assessment (LCA) is critical to evaluate whether these strategies are in fact suitable to ensure eco-friendly products, since this methodology evaluates all the environmental impacts associated to the life cycle of the products [16–18].

9.2.1 PU Foams

The majority of PU foams are thermoset polymers and are not easily biodegradable [19]. Consequently, only 29.7% is recycled, while 39.5% is recovered through energy recovery and 30.8% is disposal of in landfills [20].

The use of mechanical recycling is a simple and cheap process which can be an opportunity to increase the eco-efficiency of the polymers. Using this methodology, PU foam wastes can be used to produce agglomerates, however the market is very limited and so is the added value [21–24]. In turn, in chemical recycling, polymer wastes are depolymerized, being the recycled products used to produce new materials [7]. Despite of the necessity of equipment’s, energy and reactants, this option affords chemicals that can be used in the production of several/different materials. Hence, this route can be economically advantageous. In fact, there are several thermo-chemical methods that can be used, such as hydrolysis, aminolysis, alcoholysis or glycolysis [25]:

i. Hydrolysis of PU uses overheated steam which hydrolyzes urethane bonds leading to the formation of polyols and amines [26]. Afterwards, purification is required, being the recycled products used as raw materials for PU production.

However, the purification step is costly, making the process not economically attractive;

ii. Aminolysis is associated to the breaking urethane bonds using amines (e.g. with dibutylamine or ethanolamine). The final products are disubstituted ureas and polyols which can be used to produce new PU [27];

iii. The alcoholysis used alcohols as decomposition reactants and is based on the substitution of one hydrogen atom in water by an alcohol. The reaction is carried out in a similar way as the hydrolysis, requiring high temperature and pressure. It was developed aimed easier purification of the recycled products, but separation is nearly as difficult [28];

iv. The most used method to chemically recycle PU foams, is glycolysis, which uses high boiling glycols as cleavage agent [29]. Yet, similar to the methods described previously, it requires purification, high energy demands and long reaction times.

v. Nowadays, a new route for recycling PU scraps is emerging—the acidolysis - which converts PU wastes into a recovered polyol (RP), using dicarboxylic acid(s) (DA) [30–33]. As opposed to glycolysis, in acidolysis only one phase and no residues are obtained.

Despite of the method used, after the chemical reaction, the RP can be used as partial substitute of the petroleum-based counterparts to produce both flexible [31] and rigid [30] PU foams. Yet, the LCA results regarding chemical recycling of PUF indicate that optimization of the recycling conditions are still necessary [16–18].

9.2.2 EPS

Thermoplastics can melt under heat, hence the waste generated in the process or that resulted from the end-of-life of products can be easily recycled. In simple terms, thermoplastic wastes such as those from EPS products can be milled in to a powder and blended with cement, sand and wire mesh to produce sandwich blocks [34]. Yet, this causes a large drop in the polymer molecular weight due to thermal degradation. In addition, the ensuing material has very different characteristics when compared to the original one. Nonetheless, similar to the thermoset polymers, thermoplastic materials such as EPS can be recycled using chemical approaches.

One easy way of recovering polymers is by using appropriate solvents. These solvents must have the ability to dissolve the polymer with negligible degradation of their properties. As example, toluene was used as solvent to recycle EPS and it was proved to be more effective than benzene, ethylbenzene or *p*-xylene, at 360 ºC for 20 min [34]. Another option is to use metal-based catalysts at 300–450 ºC. Using this process styrene monomer is obtained with a high selectivity using relative low temperature. Furthermore, oxides such as MgO, CaO or BaO can be used as catalysts. In fact, using BaO it was observed a 90 wt. % conversion of PS into styrene [34].

Similarly to the PU recycling reactions, in all these chemical approaches, purification may be required.

Afterwards, the recycled products can be used as partial substitute of the petroleum-based styrene monomer to produce PS products. However, during these approaches, the material loses its cellular structure. Thus, to produce recycled EPS, it is necessary to blend the recycled PS resin with the expanding agent. This can be achieved using i.e. co-extrusion. The ensuing recycled beads can be molded into new and recycled EPS products [34].

Similar to the approach used in PUF, LCA is essential to evaluate the benefits of the recycling EPS. From the results available in literature, it can be observed that the manufacturing process of EPS is the major contributor of the overall environmental impacts while recycling has the lower impact. From these observations, it is concluded that recycling is in fact a suitable alternative to the disposal of EPS wastes [35, 36].

9.3 Other Alternatives

Whilst recycling tends to be environmentally preferable, energy recovery via incineration can provide valuable energy while hazardous additives are safely destroyed. Incineration for energy recovery can be in fact a viable alternative to recycling because it enables to generate substantial amounts of energy, since polymers have higher calorific value than coal and approximately the same value as fuel oil [9]. In addition, energy recovery can be the only suitable disposal method for wastes which do not have market. In fact, waste-to-energy and other thermal processing routes, such as gasification, pyrolysis and combustion has contributed for the disposal of significant amounts of PU and PS foam scraps [25, 37]. There are several contributions on literature regarding the energy recover from construction foams, however it is not used to produce new materials. For that reason, since it falls out the scope of this review, this alternative will not be further discussed.

9.4 Life Cycle Analysis

Environmental assessments are critical to evaluate the viability of the circular economy strategies. This tool is crucial to evaluate if the circular economy strategies contribute to the production of more eco-friendly products or not. This can be achieved by using the life cycle assessment (LCA) methodology, which complies and evaluates the inputs, outputs and environmental impacts of a product throughout its life cycle.

Lindstrom et al. [38] evaluated the EPS handling system and several disposal alternatives using LCA. While a closed-loop reuse system for EPS was most environmentally desirable, the study results indicated that conventional recycling of EPS is the only disposal scenario that generates net environmental benefits while also being logistically feasible. In a similar manner, Quinteiro et al. [16] conducted the LCA of different strategies to produce rigid PUF, including the use of recovered polyol as partial substitute of the conventional petroleum-based counterparts. It was claimed that the environmental impacts from the polyol recovery via acidolysis exceeded the environmental benefits of PUF produced using partial replacement of virgin polyol by the recovered polyol. In turn, Marson et al. [39] conducted the LCA of PUF from polyols obtained through chemical recycling, reporting that the use of recycled polyol obtained via glycolysis can contribute to the reduction of the potential environmental impacts of PUF when compared to the use of virgin polyol, provided that physical and thermal characteristics are guaranteed.

The discrepancy of results highlights the need to carry out further studies to improve the environmental performance related to recycling processes.

9.5 Challenges and Future Perspectives

Despite recycling is not the top option in the waste hierarchy, efficient recycling is widely acknowledged to mitigate the negative effects of plastic wastes. Yet, the recycling faces different challenges, and it must be continuously improved.

As previously shown, the recycling methods are very sensitive to the type of polymer, hence, separation of the different type of plastics make its recycling easier. In addition, the presence of contaminants in the waste streams, such paper, metals, glasses, or organic matter difficult the plastic recycling. For these reasons, sorting is a current challenge that foam recycling is facing. To resolve this problem, recycling facilities are being implemented at production sites to manufactures recycle their production wastes. Yet, this is not a solution to the end of life of products, which can be minimized by legislation on the waste management. Another issue associated to the recycling of foams, specially via chemical methods is the fact that these processes require high energy demand and chemical reactants. Hence, in the future the use of renewable energy and bio-based chemicals will improve the sustainability of the recycling of plastics.

9.6 Conclusions

Polymeric foams used in construction on them are mainly produced using PU or PS resins and different recycling methodologies can be used. The simplest way to recycle these materials is using mechanical methods i.e. mill them and reintroduce the ensuing powder in the production process. However, using this method, the ensuing materials has very different properties when compared with the original foam. In turn, both PU and PS foams can be recycled using chemical methods. Different routes can be found in literature, being the reaction products used to synthetize recycled PU and PS. Nonetheless, further developments are still required to ensure the sustainability of these materials. As example, mechanical recycling is not suitable to obtain value-added products and the environmental impacts associated with chemical recycling can exceeded the environmental benefits of producing materials from recovered raw materials. Following the ambition for a sustainable future, this overview aimed to highlight the benefits and challenges of the recycling of construction foams, contributing that way to the knowledge available about the recycling construction foams.

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