

Styrofoam Recycling: Relaxation-Densification of EPS by solar heat

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The problem of Styrofoam waste is multifaceted. Not only do we need to properly handle the current and future stream of newly manufactured Styrofoam objects, we also have many decades of inert Styrofoam occupying a large fraction of both our active and full/decommissioned landfills, and floating in our oceans and waterways. Solutions are therefore required for recycling current waste streams as well as mitigating huge volumes of legacy Styrofoam waste, distributed globally wherever human populations, landfills, waterways, terminal lakes, reservoirs, or ocean gyres exist. Simply banning Styrofoam, aside from packing peanuts, has been of limited effect because Styrofoam is simply too useful and inexpensive. It is essentially a super-material that is hard to replace and difficult to do without. Every environmentalist who owns a modern television unpacked it from a Styrofoam shell inside a large cardboard box.

Polystyrene, the fundamental constituent of Styrofoam, is a common plastic that recycles well. The problem with recycling Styrofoam is that as a foam it is about 98% air by volume, so it must be densified before transport for recycling: the air has to be removed from the foam to return it to its original form as a solid plastic again. The shipment of un-densified Styrofoam for recycling is not economically viable, it would take about 50 trucks to transport only one truck load of fully densified plastic. This equates to un-densified Styrofoam costing more money for paying the costs of factors such as fuel for the vehicle, more drivers, etc. This means, waste Styrofoam must be densified at or near the point of its end-of-use.

The focus of our experiments was to see how well zero-carbon, widely distributable methods of heat exposure could densify different types of expanded polystyrene packing peanuts. We show that this can readily be accomplished using the range of temperatures achievable by a typical solar oven (at or above 300°F) — well below the melting temperature of polystyrene (~ 500°F).

Rather than using solar heat for this experiment, the proof of concept was demonstrated in a temperature-controlled laboratory oven to maintain well-controlled and stable temperatures to allow the generation of accurate temperature-time-densification curves.

At the highest temperatures (~ 300°F) and the longest exposure time (10 minutes), the densification factor ranged from 50 to 53. This is very close to the theoretical limit. Lower temperatures result in partial densification with higher variability. Larger pieces would need longer heat exposure times.

To achieve full densification, we suggest using a temperature of at least 300°F (149°C) for 10 or more minutes, for pieces of Styrofoam about the size of packing peanuts. This is easily achievable in solar ovens

This process can be readily done in distributed locations at or near the location of end-of-use for Styrofoam products wherever solar ovens can achieve temperatures of about 300°F,

thereby making the recycling and upcycling of Styrofoam economically viable for most inhabited regions of the globe, and especially in equatorial areas where plastic waste is especially troublesome.

Introduction

Styrofoam is expanded polystyrene (EPS), a very commonly used industrial polymer foam which has remarkable properties and is nearly immune to weathering and natural break-down. Styrofoam weighs almost nothing, is strong and impact-resistant, costs very little, and can easily be processed into basic forms (sheets, rods, tubes, blocks, complex and detailed molds, and “popcorn”) which span the range from simple disposable shapes to complex and durable finished products. Styrofoam has an enormous range of applications: packaging; flotation devices; building construction; insulation and moisture barriers; sound, vibration, and noise isolation; components and elements for ultra-light structures; prototyping of all sorts. Its high strength-to-weight ratio, formability, ultra-low density, and environmental durability make Styrofoam a highly useful material while it remains in service. But these same properties have created an unsolvable nightmare for recycling this highly versatile, inexpensive, and durable material. As a result of its durability, combined with ubiquitous use and low density, Styrofoam has become the single most troublesome plastic from the point of view of global environmental impact [1].

How big is the problem?

14 million tons of polystyrene products are used annually. When disposed of, 68% and 20% enter landfills and oceans, respectively. Landfills are essentially graveyards for Styrofoam; approximately 30% of the volume of landfills (2.3 million tons) are taken up by Styrofoam products. Managing Styrofoam waste comprises the single largest contribution to the cost of ocean cleanup. About 18% of ocean cleanup costs are related to removing polystyrene from the seas. EPS is an extremely abundant plastic in many bodies of water [2].

Unfortunately, only 12% of Styrofoam products are recycled. In the face of these facts, and despite strenuous efforts to ban or phase out the use of Styrofoam by environmentalists, the commercial value of Styrofoam use is expected to grow to \$75 billion by 2023 [3]

Why has Styrofoam proven to be so difficult to recycle?

The process of recycling polystyrene polymer is relatively straightforward, but almost 90% of EPS is not recycled because of its uneconomical transportation cost. This is because in its expanded form it has extremely low density. It takes too many vehicles to transport a given mass of Styrofoam waste to a centralized facility for recycling. The ultra-low density of polystyrene in the expanded state (EPS) is the main problem with EPS recycling.

Thus, the fundamental reason for the Styrofoam recycling problem is fiendishly simple: The density of Styrofoam is simply too low to ship economically for recycling. Finished goods of Styrofoam are valuable and thus worth the cost of transportation. Ironically, it is the very nature of light-weight Styrofoam objects that makes the resulting products easily and inexpensively transported. But at the end of the product life cycle, the items themselves have little or no remaining value. So it is down to the intrinsic value of the material itself, not the finished product. Chunks of broken used Styrofoam have very low value per unit volume because EPS is often expanded by a factor of up to about 50, so they contain very little polystyrene polymer, which itself is a low-cost polymer to produce. A single truck load of full-density polystyrene polymer would occupy 50 full trucks when it is in the expanded form. For this reason, the cost of shipping Styrofoam to a central facility for recycling is simply too great for the recycling of EPS to be economically viable.

Attempted solutions:

Potential solutions have been proposed for decades. Yet the solutions for this problem have not really been brought to scale for consumer and disposable products because they are either not practical, safe, or economically viable. Styrofoam can be recycled on an industrial scale using large and extremely expensive EPS Densifiers: massive machines that melt, crush, or both, to densify Styrofoam. These very large machines are expensive to own and operate. They are energy-intensive, generally requiring relatively high temperatures above the minimum softening temperature to achieve flowability, and/or very high crushing forces achieved typically by large mechanical screw mechanisms or hydraulic rams. They create noise, vibration, and fumes. This approach can sometimes be viable if the Styrofoam is generated in large quantities at the location of future densification (no shipment required while expanded), and can be obtained in a form that is clean and free of contaminants. Once these industrial EPS densifiers melt and/or crush the Styrofoam, they mold or extrude it into large dense logs or blocks that can be shipped at much higher density, and therefore economically, for regrind and recycling [4].



Figure 1. A typical industrial EPS densifier, which uses high temperatures and mechanical screws to simultaneously melt and crush clean EPS into large billets for recycling.

But industrial EPS densifier technology is only viable where large quantities of clean Styrofoam are located to be recycled prior to shipment. Collecting and shipping small amounts of widely distributed Styrofoam to these facilities for densification is the step that has eluded a viable, affordable solution. This generally means that most consumer Styrofoam products and packing material are simply not viable for recycling.

To address these challenges, several other approaches have been proposed. One example of a method for densification of EPS is to use solvents, such as acetone, then allow the solvent to evaporate. This is not widely accepted because it is both costly and somewhat dangerous. The cost of the acetone alone would exceed the value of the densified polymer. A better solvent was reported by Noguchi et al. [5], which involved a natural solvent, *d*-limonene, as a shrinking agent. This is generally done at a large, specialized facility, so it does not address the fundamental problem of first getting waste EPS transported back to a large central facility for processing. The densification needs to occur at or near the point of use or collection for any approach such as this to be

economically viable.

The use of heat to shrink EPS seems logical, but Kan and Demirboga [6] report that there had been inadequate reports of the use of thermal energy to modify EPS waste prior to their report in 2009, and that the literature focused mainly on the use of high temperatures (around 450 °C) to degrade waste EPS into fuels. Kan and Demirboga then go on to discuss the use of partially-densified EPS as an aggregate for use in concrete.

Outright bans in many areas on the use of Styrofoam packing peanuts have spared us from the experience of “snowstorm in summer” that was common a few decades ago, when large swirls of packing peanuts could be seen on windy days alongside major roads in some areas. But aside from extreme measures, we have simply failed to find a viable method for managing Styrofoam waste. This can be proven by simply having a look around.

A quick survey of our local Recycling Center: How do they handle Styrofoam?

We (the authors) live two miles from a large recycling collection site in central North Carolina. The facility is modern and well-designed. It has 24 different stations and dumpsters for every classification of waste. Batteries, motor oil, household chemicals and of course bottles and cardboard are all separated and managed efficiently. However, Styrofoam waste, even in large volumes, is handled as “general household waste”. It is compacted along with bagged trash, and goes straight to the landfill. Just because there were not enough dreadful events happening around the world in early 2022, we decided to visit our local recycling center on consecutive days to observe how much Styrofoam was being “recycled” as trash, destined for the landfill (Figure 2). We made observations at 2:00 pm on seven consecutive days. On two of these days, Styrofoam was the largest visible amount of waste material in the “General Household Waste” compactor, and was also present in smaller amounts every day during the observation period.



Figure 2. A typical trash-compactor load of Styrofoam recycled as “General Household Waste” on day 2 (left) and day 5 (right) of the 7 consecutive days of observation. On day 5, the waste Styrofoam had to be divided into smaller loads and the hydraulic compactor had to be operated three times to press the large amount of Styrofoam, some of it bagged, into the compaction dumpster, headed for the landfill. Observations were made during the early afternoon on seven consecutive days of operation of the recycling center (they are closed on Wednesdays) in March 2022 at the Recycling Center on Eubanks Rd., Chapel Hill, NC. This is in a city with a well-organized, well-monitored, comprehensive recycling system with broad community support.

Survey of all 100 counties in North Carolina: Do they recycle Styrofoam?

Orange County is certainly among the most progressive and environmentally-minded counties in North Carolina, so the next logical question was whether the handling of Styrofoam waste in

Orange County was representative of how this waste is handled in other areas of the state. To determine the disposition of Styrofoam waste in recycling and landfill facilities across North Carolina, we studied the web pages and recycling policies for all 100 counties in the State of North Carolina. Of the 100 counties, only four had facilities for recycling Styrofoam or collecting it at a special drop-off point for processing elsewhere. The remaining 96 counties either specifically compacted Styrofoam along with ordinary household trash for dumping into the landfill (70), prohibited Styrofoam in their recycling and landfill under threat of fines (3), or made no mention of Styrofoam in their waste handling and recycling policies (23). The latter two categories can be assumed to place county residents into the position of casually discarding Styrofoam as household trash, surreptitiously adding it where prohibited, commingling it in small amounts with ordinary trash in the hopes of going unnoticed, or just illegally dumping it.

Re-defining the problem:

Any practical solution to the EPS recycling problem will allow widely dispersed Styrofoam objects of various size, shape, and condition to be densified at the point of end-of-use or disposal without the need for industrial solvents, high heat, or the application of external mechanical energy. The densification process itself must be safe, convenient, and simple, ideally utilizing no power from liquid fuels or from the electricity grid. The processing equipment would need to be extremely low maintenance and low cost with no special materials, and must have a relatively small physical footprint, thus allowing it to be used almost anywhere.

Addressing this problem, we first challenge the basic assumptions that have been used in the design of commercially available industrial-scale EPS densifiers:

1. Does EPS densification really require high (melting) temperatures?
2. Does EPS densification really require external mechanical compression?

Our initial thought was that some amount of EPS densification could be achieved at temperatures only slightly above the softening temperature of polystyrene, which is generally reported as 212 °F (100 °C). This is because we hypothesize that the polystyrene molecules are essentially frozen in shape at room temperature but remain under mechanical pre-stress at the molecular level because of the expansion and foaming process. Therefore, when brought to temperatures slightly above their softening temperature, which is significantly below the melting temperature of polystyrene, the PS molecules would naturally relax, resulting in some amount of natural densification requiring neither high temperatures nor the application of external compressive forces. Most importantly, the softening temperature of PS is well within the range of temperatures generally considered to be “low-grade heat”, defined as the surplus or waste heat resulting from the thermodynamic inefficiency of industrial processes, which is typically below 450°F (232°C) [7], and as such would be available widely as a no-cost industrial/mechanical byproduct. To be achievable in a solar oven, the required heat would need to be somewhat lower even than this, typically at or below about 320°F (160°C).

While low-grade heat is widely available at generally low or no cost, accessing it can be challenging, because it is hot enough to cause injury, and so is typically insulated from the general public. Examples of low-grade heat include such things as engine blocks and exhaust systems of running vehicles, heat escaping from cooking or industrial processes, and escaped heat from furnaces, motors, boilers, etc. It would be difficult to access a source of excess heat in most public spaces. Sunlight, however, is available everywhere and can be harvested year-round even in winter for solar water heaters and solar cells.

The question then becomes: can EPS be densified at temperatures and time exposures typically available in simple, consumer-grade solar cookers? While solar ovens for food preparation (cookers) are designed for a different purpose, their general designs and performance specifications are a good guide for the temperatures that are achievable for the basic types of solar ovens that are easy

to build or are readily available. Solar ovens basically fall into four categories.

Panel cookers are made using simple flat reflective panels, and generally reach about 250°F to 300°F (about 120°C to 150°C).

Box Cookers have more flat panels arranged to collect more sunlight into an insulated box, and can reach temperatures up to about 400°F (204°C).

Tube cookers concentrate the solar energy onto a tube which reaches inside temperatures up to about 550°F (290°C). The heated tube would facilitate “flow-through” processing of EPS, but in general, solar oven tube diameters are small, often just a few cm. These have been optimized for cooking small amounts of food at high heat, but could be optimized for other uses.

Parabolic cookers use parabolic reflectors (no surprise) to focus all of the collected light to the focal point of the parabolic reflector, achieving very high temperatures in the range of 500°F to 700°F (260°C to 371°C), but the heated volume is typically quite a bit smaller than the other three configurations.

The first two types of solar cooker (panel and box cookers) are quite simple and inexpensive to make and are easily scalable to the desired size and shape, so they would be well adapted to design optimization for a solar furnace specifically designed for densification of EPS. The third type, a tube cooker, can easily achieve the needed temperatures and may have the advantages of delivering more power per unit volume of heated chamber, allowing for more rapid heating and the densification of larger amounts of Styrofoam per unit time, while also facilitating a “flow-through” design for more convenient processing of a continuous waste flow of Styrofoam. Also, tube-type ovens would be more likely to operate well during sub-optimal solar conditions, such as partly cloudy days and operation at higher latitudes.

The final type of solar cooker (parabolic), while achieving higher temperatures, is considerably more expensive to build, more complex to operate and maintain, and is not as flexible in size and shape as the other three basic types. Parabolic oven configurations should only be selected for design optimization if they are required to achieve sufficient heat generation.

What is required?

The question is: what are the optimal temperature and time conditions for a solar oven prepare to achieve maximum EPS densification?

There is some initial guidance on this. Kan and Demirboga [6] report that EPS can be densified by a factor of about 20 with the application of heat at 266°F (130°C) for 15 minutes. This was reported to be their optimal result of a range of temperatures and times to generate partially-densified EPS. They designate the resulting product “modified waste EPS (MEPS)”, for use as a filler for construction materials such as concrete. More recently, Bicer [8] reported that EPS could be densified for recycling into construction aggregates by a similar application of heat, optimally 125°C (257°F) for 15 minutes, which achieved a densification factor (volumetric reduction) of ~12.

These reported low-heat densification results were primarily done to generate aggregate for use as a concrete filler, so the primary consideration was densification of EPS to achieve optimal mechanical strength while retaining some insulation properties. Therefore, some amount of residual air content in the volume-reduced EPS is desirable, and thus, the absolute highest level of densification was not optimized for in these studies. However, to optimally prepare EPS for transport and recycling, achievement of maximal density is the objective to economize on the cost of transport per unit mass of PS polymer. Therefore, the second question is: under optimal conditions, what are the limits for low-heat densification of EPS? This is easily estimated by calculating the ratio of high-density polystyrene polymer to the density of the expanded polymer.

The density of solid (non-expanded) polystyrene is 1060 Kg/m³.

The density of EPS varies widely in the range from less than 20 up to about 50 Kg/m³, depending upon the application and intended use. Higher density EPS will of course have greater strength and durability than lower density EPS [9].

Then, the upper limits for EPS densification is easily calculated as:

1060 ÷ 50 = 21 for EPS with the greatest density and strength, such as structures, containers, fillers for void spaces in mechanical elements, durable insulators and flotation devices.

1060 ÷ 20 = 53 for EPS with the greatest expansion traded off against strength, as typically used in packing peanuts and other very low-density Styrofoam.

Based upon this, our questions are:

1. Can EPS be densified simply by applying low-grade heat for a sufficient amount of time
2. What is the level of densification that can be achieved without the addition of externally applied mechanical force? Does it approach the theoretical limit of densification?
3. What amount of time, heat, and external mechanical pressure does the densification process require?

Then, based upon results from the above, we ask finally whether recycled EPS popcorn can densify to the same degree as new (unrecycled) EPS popcorn.

Methods

For the initial proof-of-concept experiment (Ex. 1), clean, recycled EPS packing peanuts (Excelsior) were collected and undamaged specimens were placed into groups of 4. Peanuts were tested as either virgin polystyrene (white), or partial regrind (70%) polystyrene (green). No Styrofoam peanuts were harmed in this experiment. The purpose of this experiment was to test the range of temperatures from the EPS softening point up to a readily achievable temperature for solar ovens, although a solar oven was not used because of the experimental need to carefully control and repeat the experimental temperature conditions.

An industrial/scientific laboratory-grade temperature-controlled oven was fitted with a fuzzy-logic precision temperature control module with K-type thermocouple, calibrated with an accuracy of +/- 1.8°F and allowed to stabilize at each experimental temperature (210, 230, 250, 275, and 300°F) for 30 minutes before each experiment. At a stable temperature, each group of peanuts were placed into the oven, spaced loosely in a small aluminum basting tray. Each group was held at temperature for 1, 3, or 10 minutes. Control peanuts were not subjected to heat exposure. All peanuts were then dimensionally measured using a digital caliper, the densification ratio was calculated, and the averages tabulated and plotted for each temperature and time point.

The second experiment (Ex. 2) involved the use of a single temperature and a single exposure time: 284°F (140°C) for 10 minutes. This was selected as a conservatively low temperature and time to demonstrate the minimum expected heat that could be used for this technique. The application of higher temperatures or longer times would be expected to achieve better densification, making the conditions of this experiment a lower limit “worst case” for the effective densification for this process. A purpose-designed solar oven specifically optimized for EPS densification should easily be able to achieve or exceed these densification parameters.

We tested 20 samples of each type of commonly available EPS packing peanut: pink (anti-static coated), white (new and without additives EPS), and green (~ 70% regrind recycled EPS). As

Styrofoam peanuts come in three common shapes, the shapes we tested were “s” (pink), “w” (white), and “figure-8” (green). For both experiments, no external compressive stress was applied. Therefore, the entire densification process was driven by the heat-relaxation of the polystyrene molecules as they were heated at various points above the glass transition temperature of polystyrene. Additionally, since the overall shape of each peanut was retained during heat-relaxation, the change in overall dimensions was used to estimate the total volumetric change of each peanut.

For both experiments, densification was estimated by dimensional change before and after heat exposure. Dimensions were measured using a Mitutoyo 8-inch digital caliper. Each peanut was measured by length, width, and thickness. The volume of an imaginary rectangular box of minimum dimension into which each peanut would fit was calculated. The densification ratio was calculated by calculating initial box volume divided by the final box volume.

For Ex 1, no statistics were calculated as this preliminary test was intended to give a ballpark estimate for the temperature-time-densification-peanut shape relationship.

For Ex 2, the statistical significance of differences in sample means was determined by ANOVA using the calculator available on astatsa.com

Results

The first observation, for both of these experiments, is that this low-temperature process produces no detectable fumes or odor, and no detectable residual slag-like material in any form at the temperatures and times employed. This in contrast to melting the polystyrene, which requires much higher temperature and typically results in considerable outgassing of fumes and charring with denaturation of the polymer.

Experiment 1: Representative images for peanuts held at temperature for 0 (control), 1, 3, and 10 minutes are shown in [Figure 3](#) and [Figure 4](#). The peanuts retained their shape and approximate dimensional proportions, and densified solely due to the relaxation of internal stresses when held at temperatures above the softening temperature. The results are shown in [Figure 5](#).

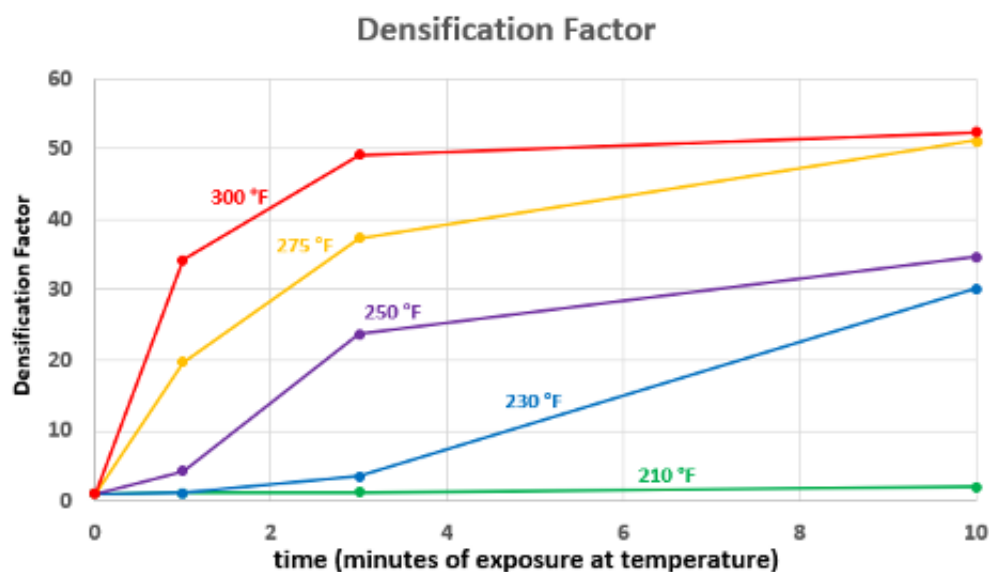


Figure 3.

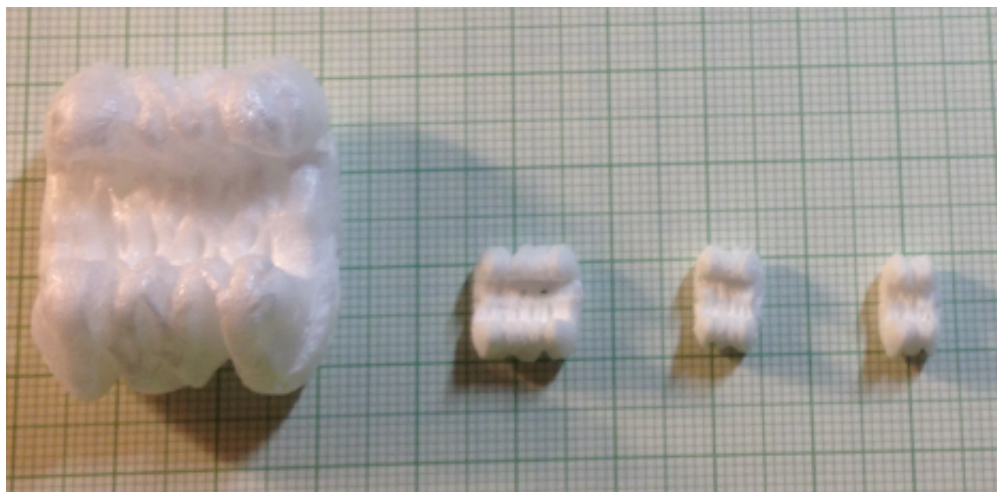


Figure 4. new, without additives EPS (white “w” shape) at 275°F for 0, 1, 3, and 10 minutes. Grid is made up of 1 cm large and 1 mm small squares.

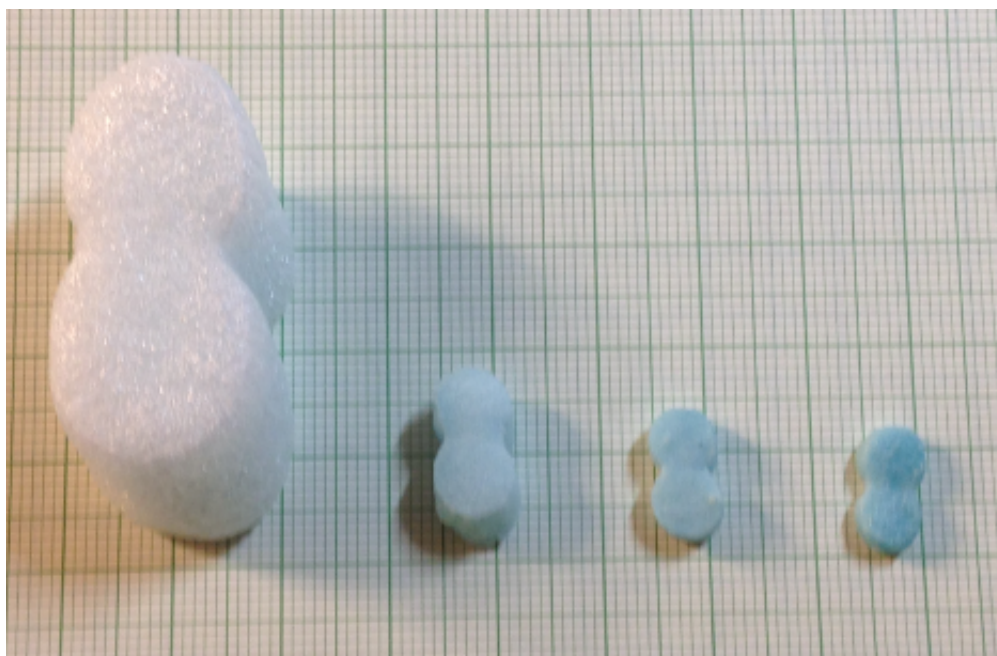


Figure 5. 70% regrind recycled EPS (green “figure-8” shape) at 300°F for 0, 1, 3, and 10 minutes. Grid is made up of 1 cm large and 1 mm small squares.

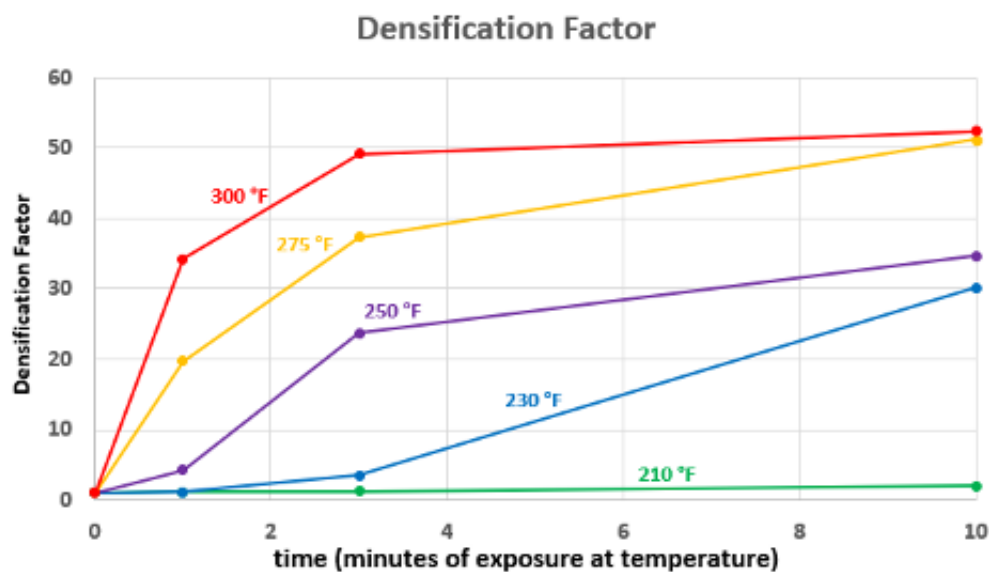


Figure 6. Experiment 1: Temperature-time-densification curves for EPS peanuts for times of 0 (control), 1, 3, and 10 minutes of exposure to temperatures of 210, 230, 250, 275, and 300°F.

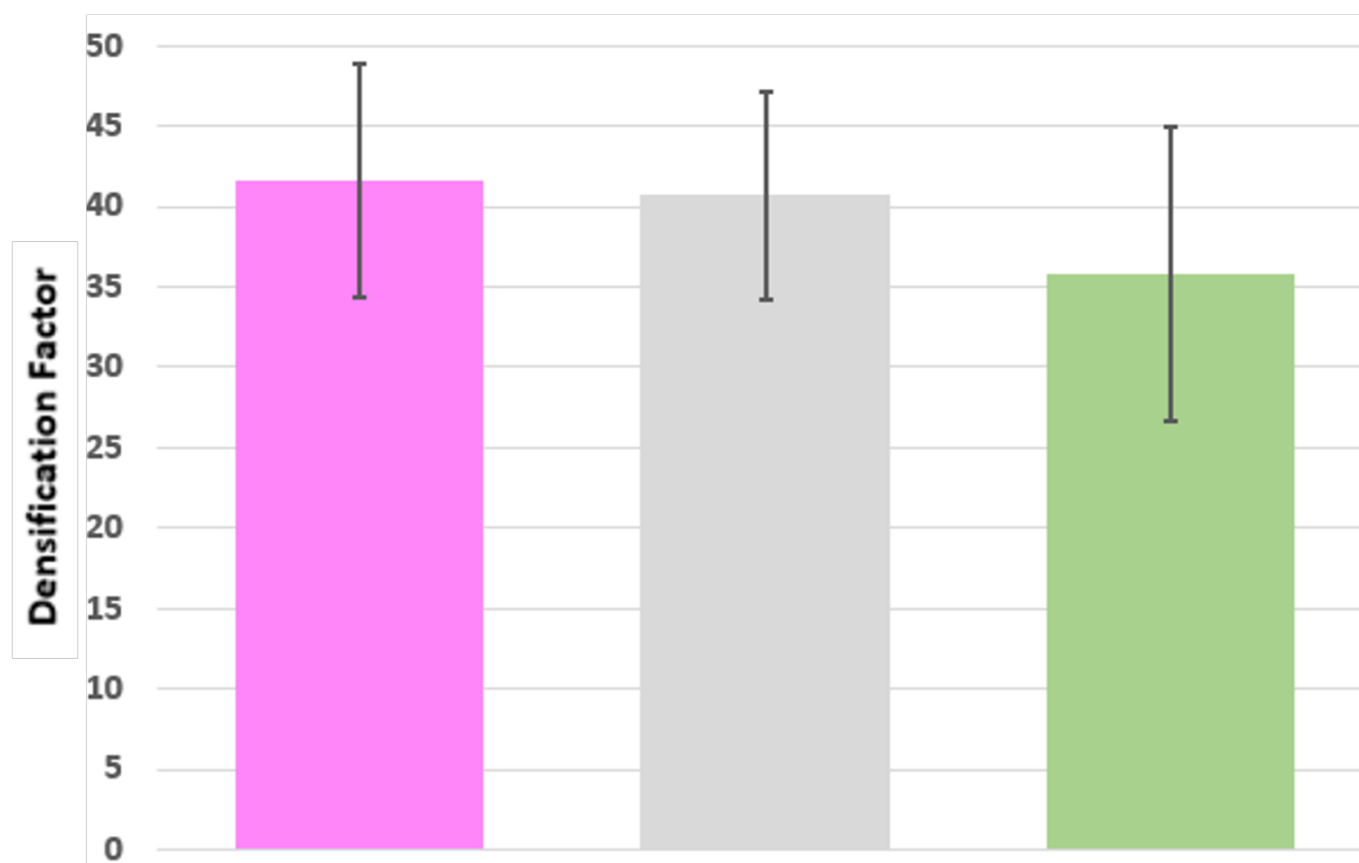


Figure 7. Experiment 2: Densification of 20 samples each at 284°F (140°C) for 10 minutes for pink (anti-static, "s" shape), white (new and without additives EPS, "w" shape), and green (70% recycled EPS, "figure-8" shape) Styrofoam peanuts.

Experiment 2: Without heat exposure, the densification of the samples is defined as 1.0. Twenty samples of each of the three types of EPS peanuts (pink, white, and green) were initially measured (length, width, and thickness), heat softened, cooled, and measurements taken to determine the volume change.

An ANOVA was performed using the online calculator at astatsa.com, followed by a post-hoc Tukey calculation, with the following results ([Figure 8](#)).

treatments pair	Tukey HSD Q statistic	Tukey HSD p-value	Tukey HSD inference
A vs B	30.0886	0.0010053	** p<0.01
A vs C	30.2889	0.0010053	** p<0.01
A vs D	30.3956	0.0010053	** p<0.01
B vs C	0.1635	0.8999947	insignificant
B vs D	0.2506	0.8999947	insignificant
C vs D	0.0871	0.8999947	insignificant

Figure 8. The mean volume (or densification factor) of the control (group A) is significantly different from all densified sample group means, but there is no significant difference in the densification between any of the three densified groups (B, C, and D; which are anti-static, new, or 70% recycled EPS, respectively).

With the application of heat above the glass transition temperature but well below the melting temperature for PS, the samples soften and self-densify to about 35 to 41 times their original density as estimated by minimum box size volume change. Mean and standard deviation bars for the densification factor are shown for each group in [Figure 7](#).

Discussion

Under the range of tested conditions (210 – 300°F for 3 to 10 minutes), the relaxation-densification of EPS popcorn through thermal softening and the unforced relaxation of internal polymer chain stress achieved remarkably high levels, nearing the theoretical limit, with densification factors in the range of ~ 52 in Ex. 1 for the highest temperature (300°F) and longest exposure time (10 minutes), and a densification factor of ~ 35 to 41 for Ex. 2, using a conservatively low and readily-achievable temperature (284°F) and exposure time of 10 minutes. Experiment 2 is intended to demonstrate the effectiveness of this low-grade heat relaxation-densification method by selecting a temperature and exposure time at the very minimum range for each that would be easily achievable in a solar oven. Even under these “worst-case” conditions, the densification was greater than 35, and typically greater than 40, which is still excellent for commercial recycling requirements.

The demonstrated achievable volumetric change (densification) is both statistically significant and commercially important for the viability of EPS recycling. Even under the least favorable conditions of time and temperature, the demonstrated level of densification is very competitive with or is superior to the densifications achieved with the best commercially available EPS densification equipment.

The process we describe only requires low temperatures in the range of 300°F, and is easily achievable in solar ovens and from low-grade industrial heat sources. For small pieces of Styrofoam, this relaxation-densification occurred within 10 minutes, in a free-convection low-temperature oven. Larger pieces would be expected to require more time owing to the excellent thermal insulation properties of Styrofoam itself. So, for a practical process, this process might require the waste Styrofoam to be broken or cut into smaller pieces before densification in a solar oven.

An advantage of using solar energy over low-grade heat from other sources is that when the sun shines, it may be harvested for both solar heat and electricity. This could be very convenient, because one of the major limits to solar ovens is that they do require constant adjustment for the

angle of incident light, and this would allow the addition of a low-cost solar-powered electrical heliostat mechanism to point the oven reflectors. Also, solar energy is a variable source that is influenced by weather and time of day. Therefore, the process will be improved if we can apply basic process controls to prevent such events as system overheating, which is also a risk if high-quality PS polymer is desired for upcycling. Process control would be easy to implement using very inexpensive and widely available embedded microprocessors (such as Arduino) with basic sensors and actuators, commonly used in DIY and STEM robotics kits. This would allow, for example, the opening of cooling vents or adjustment of reflector panel angles to prevent overheating, or the slow rotation of the solar reflectors to maintain maximal use of solar energy throughout the day (a heliostat). Simple temperature, time, and energy flow control allow for vastly improved process control and will yield superior results by maintaining system setpoints as near as possible to optimal values.

The final question related to the densification of popcorn made from 70% regrind recycled EPS as it compares the densification factor of new EPS with no recycled content, under the same densification conditions. Statistically, recycled EPS densified as well as new EPS even at very low temperatures.

This simple method of densification works at modest temperatures because EPS products are used below the glass transition temperature of polystyrene, generally taken to be about 100°C (212°F). Above the glass temperature (T_g), polystyrene chains will begin to flow, even well below the melting temperature (T_m). During the expansion process, EPS is essentially frozen into shape and retains that shape so long as T_g is not exceeded during the service life of the EPS product. Below T_g , the polystyrene polymer chains remain frozen in their pre-strained state as a foam with entrapped air. Above T_g , the polystyrene polymer chains will begin to relax, and as they do so, visible gaps open on the surface and within the foam structure to release the trapped air within. Being neither constrained by temperature nor by internally trapped air, the polystyrene chains continue to relax, expel entrapped air, and the foam densifies to very nearly a solid block of polystyrene.

Raw data are available upon request, however, this experiment is very easy and inexpensive to replicate.

Conclusions

Even though efforts to ban Styrofoam have been extensive, strenuous, and ongoing for decades, Styrofoam remains a commonly used material in many applications because it is an excellent material (its environmental impact notwithstanding) and a more environmentally friendly material that is both cost- and performance-competitive has not yet been found.

Using only low-grade heat, Styrofoam will self-densify. No additional external forces are required. A temperature of only 284°F (140°C) for 10 minutes yielded very good densification of at least 35, and typically 40. The application of slightly higher temperature (300°F, 149°C), yielded densification typically at or above 50, very near the theoretical limit, which is equivalent or superior to the densification achievable with the best large and costly commercial energy-intensive EPS densifiers. The advantage of these large commercial EPS densification systems are mainly throughput speed for continuous EPS processing at a dedicated facility. Such systems are generally not cost effective or practical for point-of-use or intermittent use applications.

While EPS initially densifies quickly when exposed to heat at or above ~275°F, higher temperatures and longer heat exposure periods are required to achieve full densification.

While new (unrecycled) EPS in small pieces (packing popcorn) readily densify to near the theoretical limit at 300°F with ten minutes of heat exposure, temperatures slightly above 300°F for

longer than 10 minutes might be required to achieve full densification for larger pieces of EPS, or recycled EPS.

There were no significant differences between the densification factor achieved for any of the three groups (anti-static, new without additives, or 70% recycled EPS, respectively). The green (70% recycled) EPS did have the visual appearance of achieving less densification than new, non-recycled EPS, but the difference was not statistically significant, owing to the larger variability of the densification of the 70% recycled EPS at this temperature. It is not known if higher temperature or longer heat exposure would reduce this variability while shifting the mean toward higher densification, or whether the samples would simply have settled toward a mean densification factor as low as that for new and additive-free (white) EPS. Nonetheless, it is probably advisable, especially when densifying older or recycled EPS, to plan for slightly higher temperatures and longer exposure times.

The potential uses of this low-temperature relaxation-densification process include both point-of-use recycling, as well as in the low-cost, high efficiency remediation of landfills and ocean waste. Additionally, the resulting densified EPS while still heated above T_g remains soft and flowable. It could be molded on-site using simple press-molds into simple forms for up-cycling to create durable polystyrene objects, or it could be shipped and recycled, or used directly as a concrete/asphalt filler material.

We conclude that low-cost EPS relaxation-densification can be done manually or could be easily automated with very minimal sensors and embedded controllers/actuators. Simple solar ovens with the necessary performance can be constructed using materials and technologies available in even the poorest areas of the globe, allowing the handling, recycling, and remediation of Styrofoam waste in any location where adequate levels of sunlight or low-grade heat is available.

Summary

Small pieces of Styrofoam (EPS), the size of packing peanuts, can be fully densified at 300°F (149°C) in ten minutes for pieces only a few cubic centimeters in size when expanded. A simple solar box cooker with flat reflective panels will be adequate for this purpose, and can be optimized for EPS densification rather than for cooking food.

At lower temperatures, high densification can be achieved, but the densification is less reliable.

Slightly longer exposure times or higher temperatures may be necessary for previously-recycled Styrofoam, but note that the differences are not statistically significant.

Larger pieces (not tested) are likely to require longer temperature exposure times because of the excellent thermal insulation of EPS.

With adequate temperature and exposure time, both readily achievable using simple panel-box solar ovens ($\geq 300^\circ\text{F}$ or 149°C), EPS can be densified to very near the theoretical limit of 53 (densification factor). At this densification level, a given mass of waste Styrofoam can be transported at about 1/50th the cost of Styrofoam in the expanded state, making Styrofoam recycling much more economically viable.

Potential Conflicts of Interest

The authors are founders and officers in a newly formed not-for-profit 501(c)3 corporation registered in the State of North Carolina, SolCycle Inc., with the purpose of education, research, and outreach involving the use of solar energy to facilitate recycling and sustainability. As such, the authors declare no financial conflicts of interest.

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