MECHANOCHEMICAL CONVERSION OF FLEXIBLE PU FOAM INTO FUNCTIONAL ADDITIVES FOR CIRCULARITY

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Abstract

Discarded flexible polyurethane (PU) foam from mattresses presents both an environmental burden and a valuable feedstock for circular material innovation. This work introduces a novel mechanochemical strategy to convert waste flexible PU foam into surface-functionalized powders, which serve as high-performance additives for paints, lubricants, and polymer composites. The process employs a proprietary grinder constructed with transition metal alloys, enabling precise control over particle size and surface chemistry through reactive grinding in the presence of functional gases. This approach facilitates the incorporation of polar functionalities, significantly enhancing compatibility with polymer matrices and enabling applications in rheology modification, insulation, and composite reinforcement. The core innovation lies in the integration of mechanical grinding with in-situ chemical surface modification – establishing a new pathway for circularity in PU foam recycling. We will present performance data from our grinder prototype and demonstrate the utility of the resulting functional powders in composite formulations, including their role in lightweighting polymeric systems. This work directly supports the goals of the Mattress Recycling Council and the ReMADE Institute by transforming hard-to-recycle mattress components into functional materials, and lowering CO_2 emissions associated with conventional disposal and filler production.

Introduction and Motivation

Over 2 billion pounds of flexible polyurethane (PU) foam are used each year in the United States, 86.5 percent of which ends up in landfills or incinerators [1]. In US alone, more than 18 million mattresses (one of the largest uses for flexible foam) are thrown away annually [2]. This leads to substantial environmental damage, reduced landfill capacity because of the foam's low density, microplastic generation, and missed chances to reclaim valuable materials. Flexible foam contains high value polyols and offers immense potential for upcycling high-value products with several follow-on applications across a variety of industries.

Flexible waste foams are difficult to recycle because of their low density, toughness, elasticity, cross-linked structure, and thermal resistance. Current recycling methods, mechanical or chemical, are costly, inefficient, and yield inconsistent or low-value products. Chemical recycling focuses on polyol recovery but is energy intensive, often reduces material quality, and results in loss of urethane segments; reclaimed materials typically require post-processing and are mainly used in low-value applications, leading to underutilization.

Our approach aims to overcome these current challenges and lower costs in producing functional materials by combining shear grinding with reactive gas perfusion. Using a proprietary grinding apparatus with temperature and gas flow control, this process creates flexible foam particles with tailored particle size and surface functionalization. The modified powder can be used as a functional additive in polymer composites for automotive and aerospace applications, as well as coatings, adhesives, lubricants, and filtration media. Products containing the functionalized foam powder can also be recycled, promoting circularity and reducing landfill waste while delivering economic and environmental benefits.

Review of Related Work

Recent studies have demonstrated the potential for mechanical and chemical approaches to reduce PU to fine powders that can retain or even gain functional groups (e.g., hydroxyls or amine groups), but these systems lack integrated thermal features, gas-phase reactivity, and continuous process feedback [3], [4], [5]. These methods face challenges with limited scalability and high-value applications of recovered material due to long processing times and minimal control over the material properties of the recycled foam particles.

There is some evidence in current literature for converting mattresses into high-value products like graphite. Numerous studies have also been conducted to generate valuable end-products, like carbon precursors, for battery manufacture and additives for cement composites [6]. Significant efforts have also been made to extract polyol from urethanes via chemical means. However, relying solely on recycling foam for polyol recovery is limiting and inefficient; it sacrifices valuable components, such as the entire urethane linkage, which contains significant chemical functionality and potential value. This loss diminishes the overall material yield and does not capitalize on the material's fully embedded value. In addition, these processes require large pyrolysis plants and are highly energy intensive.

At present, no commercial technologies are capable of consistently reducing flexible foams to controlled submillimeter particle sizes. Most current mechanical methods target rigid foams and use a shredding mechanism, rather than shear-based grinding, which is a key feature of our technology.

Technology Approach

Grinding Apparatus Design & Iteration

The major innovation developed by RoCo® is the grinding apparatus designed specifically to grind flexible (rather than rigid) foams, which produces functionalized foam powder. Initial prototyping began with a proof-of-concept approach, focusing on the mechanical grinding action. We wanted to focus on shear-based grinding – this has a distinct advantage over shredding when considering reduction of flexible foams, as this mechanism applies intense lateral forces at the interface of two solid surfaces. These lateral forces overcome the threshold "grip" needed to fragment flexible foams to fine, uniform particles. Beginning with a commercially available malt grinder, we designed a textured "grinding cap" to maintain uniform spacing around each roller in the mill. After iterating such that this cap produced reliable foam reduction, we conducted a series of grinding tests that varied grinding time from 30 to 180 seconds. This trial showed an average particle diameter of less than 1 mm after at least 60 seconds of grinding, with results as small as 140 microns.

Once basic questions about the grinding mechanism were answered, we designed a second prototype to include the key components enabling surface functionalization of the foam powder: heat control and gas perfusion. The perfused gases interact with the freshly increased surface area of the foam particles and, when combined with the grinder's controlled temperature conditions, enable the incorporation of additional polar functional groups onto the surface. This approach allows for tuning of surface chemistry, which can be tailored to suit a variety of end applications where enhanced reactivity or compatibility is desired. Heating control was achieved in this version by operating the grinder in a temperature-controlled environment. The third prototype included embedded heat controls, an automated feeding system, and independently driven textured rollers. This version, however, had significant challenges with the feeding mechanism, such as jamming and inconsistent feed rates.

The final prototype, used to produce the foam powder described in later sections, features a grinding "cup" into which fit two linear rollers, each with variable diameter along their length. The variable diameter is intended to create space for large foam pieces to be "grabbed" into without jamming prior to being guided into the controlled grinding space between the largest outer diameter of the rollers and the inner surface of the grinding cup. This system also includes a gas perfusion inlet and controlled heating elements in the grinding cup. We currently manually sieve the foam powder to break up clumps that form during grinding; however, the average particle size is an order of magnitude smaller than the sieve pore size, indicating sieving has no impact on final particle size. In future scaled designs, this sieving mechanism will be automated and incorporated directly into the grinding machine.

Foam Collection & Processing

All foam powder samples detailed in the following sections were produced using shredded post-consumer mattress foam provided by the Mattress Recycling Council (MRC) to RoCo®. We varied three factors during processing trials: time, system temperature, and gas perfused. The levels for each factor are shown in Table 1.

Table 1. Grinding System Parameters

Parameter (Factor)	*Levels*
Processing time	60, 180, and 360 seconds
System temperature	25, 60, and 150 ºC
Gas perfused	N_2, CO_2

An additional high-temperature condition (roughly 230ºC) was explored in early tests but is not included in this table, as this temperature led to significant foam decomposition beyond the scope of routine processing conditions. Initially, we explored all parameter permutations to perform material characterization. However, we narrowed these conditions to a representative set for subsequent applications testing: 360 seconds, 60ºC, and perfusion with either N_2 or CO_2.

Material Characterization

Bulk Properties

The bulk properties described here pertain only to foam powder ground using our representative set of system parameters (360 seconds, 60ºC, and perfusion with either N_2 or CO_2). Figure 1 shows the resulting foam powder at both macro- and microscopic scales.

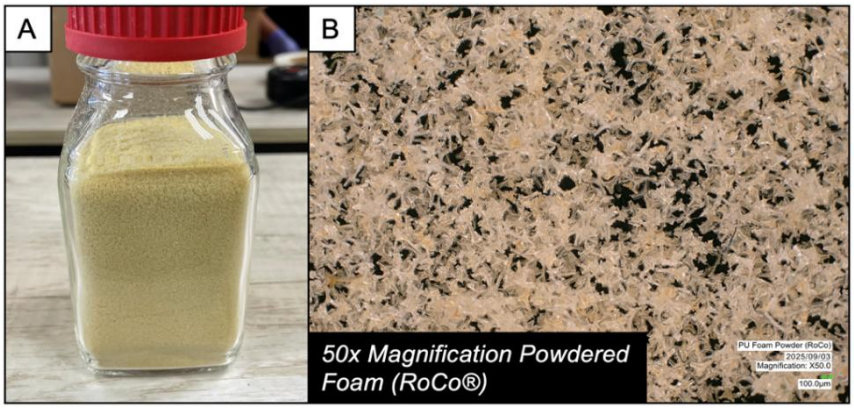

Figure 1: Macroscopic and microscopic images of the ground foam powder. (A) Ground PU foam powder as it appears to the naked eye. (B) Foam powder particles under 50× magnification.

The average bulk densities of the powders were 0.175 ± 0.0015 g/cc and 0.140 ± 0.0017 g/cc for powder processed under N_2 and CO_2, respectively. This represents a densification of roughly 10x when compared to unground foam pieces. The average particle sizes for foam processed under CO_2 and N_2 were 176 ± 2.1 microns and 167 ± 1.8 microns, respectively. Both gases yield fine powders on the order of a few hundred microns in diameter.

Material Properties

All samples were analyzed using thermogravimetric analysis (TGA) (*Discovery TGA55; TA Instruments; New Castle, Delaware*). Figure 2 shows the first decomposition temperature data for foam processed under either N_2 or CO_2 across grinding times, providing insight to the interdependence between temperature, perfused gas, and grinding time. Notably, there is a 4°C increase in decomposition temperature from foam processed at 60°C for 180 seconds under N_2 to foam processed under the same time and temperature under CO_2. This indicates the perfusion of CO_2 during grinding causes a chemical change in the foam powder that results in a more stable intermediate. This also indicates there is a combinatory effect of both system temperature and gas perfused; however, this relationship is not clearly understood with current data.

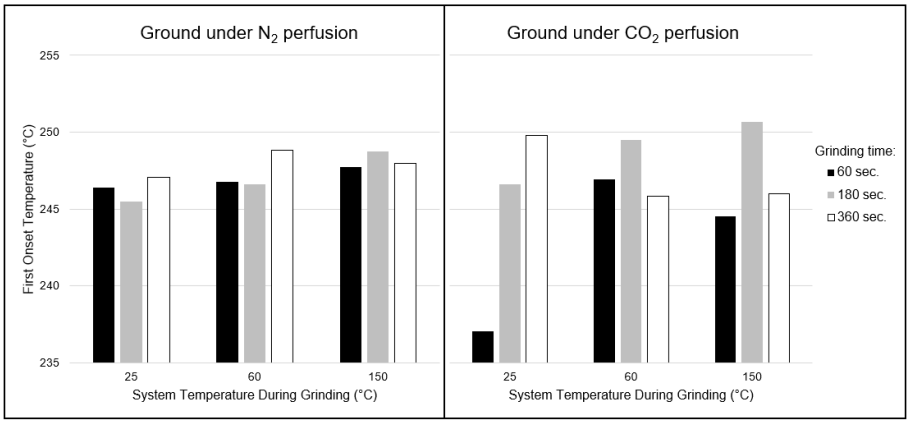

Figure 2: Decomposition of Foam Powder. The figure shows the first onset data for thermal decomposition of foams processed under N_2 (left) and CO_2 (right) across various processing temperatures and grinding times.

In addition to TGA, all samples were analyzed using Differential Scanning Calorimetry (DSC) (*Discovery DSC25; TA Instruments; New Castle, Delaware*). Figure 3 shows an example overlay obtained during DSC analysis.

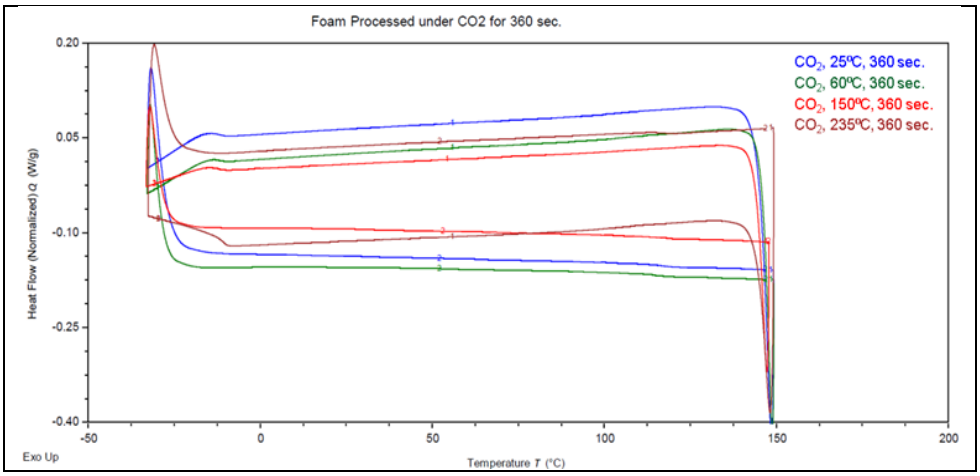

Figure 3: Overlay of Samples Processed under CO_2 across Various Temperatures. Image shows an overlay plot of DSC data gathered for samples processed under CO_2 for 360 seconds across all controlled temperatures.

Of note is that there are certain sanity checks that cannot be easily explained by this data. For example, this overlay shows a glass transition temperature near 110ºC. This would indicate that the foam feels solid/inflexible at room temperature; however, the foam is incredibly flexible at room temperature, leading us to hypothesize that the true glass transition temperature should be much lower. Similar abnormalities are present across various response conditions. This discrepancy implies the DSC could be detecting a transition that is not apparent in the foam's bulk feel, due to measurement artifacts or complex transitions in the polymer. Further experimentation, including forming pressed pellets for more uniform testing, is required to elucidate the relationship between the factors and their effect on the material's thermal properties.

Finally, we analyzed all samples using Fourier Transform Infrared Spectroscopy (FTIR) (*NicoletTM iSTM 5 Spectrometer with iD5 ATR Accessory; ThermoFisher Scientific; Waltham, Massachusetts*). For each sample, two spectra were collected and averaged to create one representative spectrum. Figure 4 shows an overlay of foam powders processed at room temperature under both CO_2 and N_2. The spectra are relatively indistinguishable, indicating that there is little to no difference in surface functionalization caused by gas perfusion at room temperature. This figure also includes a spectrum for "unground foam." The original foam chunks used as input material for grinding are a mixture of post-consumer mattress foams, meaning each has a slightly different composition. This "unground foam" spectrum was created by analyzing a chunk of each foam type available, then averaging these together. As shown, it is markedly different from each of the samples processed at room temperature. This is due to the homogenization of the foam types that occurs during the grinding process. As such, we feel the room temperature spectra are a more relevant baseline comparison for future analysis.

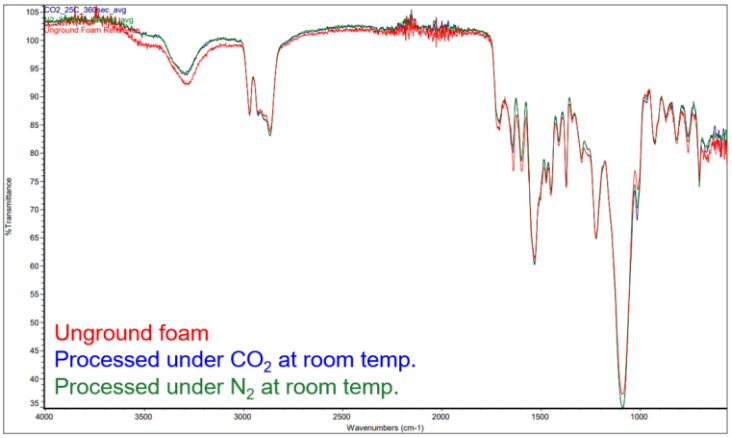

Figure 4: Room Temperature FTIR Comparison. Image shows samples processed at room temp. for 360 seconds.

When system temperature is raised (shown in Figure 5), differences in functionalization begin to emerge between foam processed under either N_2 or CO_2. These results support the conclusion that both temperature and gas type play a role in surface functionalization (both independently and interactively); these results also indicate there is likely some threshold temperature the samples must be ground at for the gas type to begin playing a role.

More in-depth spectral analysis is described below; general trends hold true for all samples. Peak assignments are based on

typical polyurethane functional groups [7], [8].

At room temperature, a slight increase in the peak near 1090 cm-1 was observed under CO_2 compared to N_2. This region is associated with C–O–C stretching in ether or ester linkages of PU [7]. The peak near 600 cm^{-1}, possibly related to out-of-plane bending of aromatic C–H or urethane linkages, was reduced under CO_2 compared to N_2. The increase at 1090 cm^{-1} suggests enhanced formation of ether/ester groups, possibly due to CO_2-induced surface oxidation. The reduction at 600 cm^{-1} may indicate disruption of aromatic or urethane structures under CO_2.

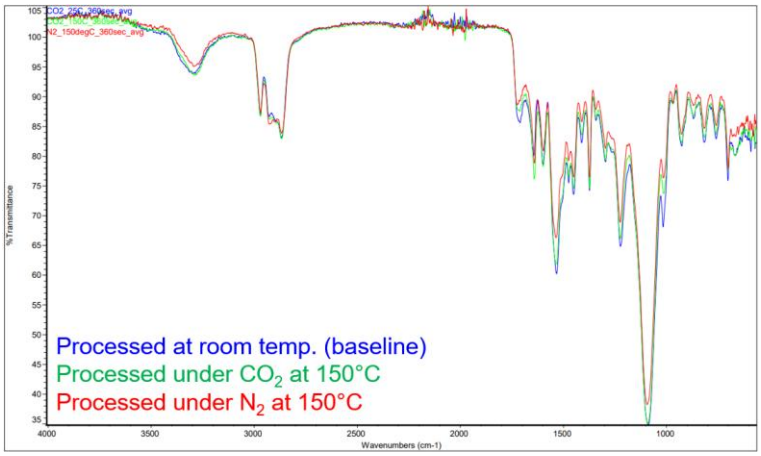

Figure 5: Gas Perfusion Comparison at Increased Temperature. Image shows overlay of samples processed at 150ºC under both N_2 and CO_2 for 360 seconds, compared with a base case processed at room temp.

At elevated temperatures under CO_2, the broad peak near 3200 cm-1, attributed to O–H stretching (e.g., from water, hydroxyl groups, or urethane N–H), sharpens with increasing temperature, particularly at 60C under CO_2. [8]. We attribute the increased intensity of CO_2 processed foam compared to N_2 sample to more available OH or NH groups. We assigned the peak near 1700 cm-1 to C=O stretching in urethane or ester groups. This peak shows an increase 25°C and 60°C but diminishes significantly at 150°C [7]. The decrease suggests thermal degradation of urethane. However, this peak increases at 60°C, which correlates with increased formation of carbonyl bonds. Finally, the peak near 1650 cm-1 is likely associated with amide C=O bonds. This peak shows significant increase under CO_2 at 60°C [8]. The increase indicates formation of amide-like structures, possibly from thermal rearrangement or oxidative degradation under CO_2.

We propose two major mechanisms to explain these changes: grinding-induced changes and thermal degradation under CO_2. Grinding under CO_2 may introduce mechanical stress and localized heating, leading to chain scission and exposure of reactive chain ends. CO_2, being mildly acidic, could react with urethane NH groups to form carbamates (R–NH–COOH) or promote oxidation. This explains the increase at 1000 cm^{-1} (C–O–C) and reduction at 600 cm^{-1} (disrupted urethane/aromatic groups). Under N_2, an inert atmosphere, mechanical degradation dominates without significant chemical interaction, preserving most functional groups. Additionally, there are numerous peak differences that suggest thermal degradation under CO_2. First, the sharpening of the 3200 cm^{-1} peak suggests loss of water, possibly from dehydration of hydroxyl groups or urethane breakdown [9]. CO_2 may catalyze this by forming transient carbamates that decompose high temperature and high shear. The decrease in the 1700 cm^{-1} peak (C=O) at 150°C and 235°C indicates decarboxylation or cleavage of urethane/ester linkages, forming volatile CO_2 and amines [10]. The increase in the 1650 cm^{-1} peak suggests formation of C=C bonds (e.g., via elimination reactions) or amide-like structures from rearrangement of degraded urethane segments. CO_2's oxidative potential at 235°C is likely enhanced by these pathways compared to N_2.

While these proposed mechanisms need to be confirmed with further targeted experiments, we believe our data clearly show that mechanochemical processing of polyurethane foams can be combined with reactive gas perfusion to achieve in situ surface chemical modification. This can be capitalized upon to tune the PU powder's properties to suit an end user's needs across a variety of industrial applications.

Applications Testing

When considering where to focus our resources for applications testing of our foam powder, we balanced value to end users and the ease of market entry for multiple use cases. We selected the following use cases to test: non-structural cementitious mixtures (e.g., sidewalks, parking lots, interior flooring, etc.), rigid foams for construction uses (e.g., acoustic foam panels, lightweighting, sound dampening in automotive noise, vibration, and hum (NVH) markets, etc.), and as a compressed particle sheet (e.g., for use as a filtration media).

Cement Additive

Cement samples were prepared by combining cement and foam powders at 5, 10, 15, and 20 percent by volume ratios for both N_2- and CO_2-processed foam powder variants. Negative control samples were prepared using only cement powder. Once the dry powder mixtures were prepared, water was added in a 4:1 powder-to-water ratio, per manufacturer instructions (*Rapid Set Cement All, CTS Cement Manufacturing Corp., Garden Grove, CA*). The samples were mixed with a drill and paddle to ensure homogeneity, then poured into silicone molds and left to dry on a lab benchtop 24 hours before demolding.

Generally, increased foam additive percentage resulted in decreased density of the cement compared to a negative control. For the samples with foam processed under N_2, there was an average density decrease of over 10 percent. While not formally quantified during this phase, the foam additive had a noticeable impact on the pouring behavior of the cement mixture; for foam powder processed under both gas types, the cement mixture became noticeably more viscous as higher volume percentages of foam powder were added. Qualitatively, we observed that the PU additives dried more quickly than the negative control samples with any amount of foam additive. The most noticeable instance of this behavior was for samples with 20 percent foam processed under CO_2 – for these samples, drying time appeared to reduce by roughly half. This property merits further exploration in follow-on research if cement additive applications become more relevant.

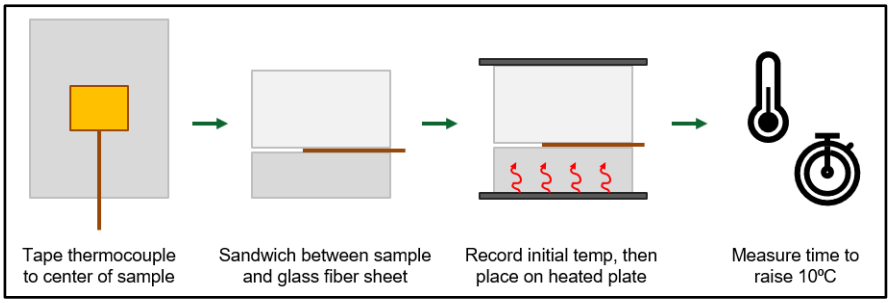

Figure 6: Summary of thermal diffusivity test. Image shows workflow used to capture thermal diffusivity data.

We also assessed impact on thermal insulative properties, resistance to salt corrosion, and paint adhesion. Thermal insulation was estimated via proxy measurement of thermal diffusivity; this test was conducted by placing a J-type thermocouple to the center of a cement sample, placing a glass fiber insulating sheet on top of the thermocouple, placing the sample on top of a controlled-temperature plate, then recording the time it took for the thermocouple temperature to rise by 10ºC (Figure 6). Generally, there was no difference between foam additive types (processed under N_2 vs. CO_2). However, there was a difference when considering foam additive percentage. For samples with low additive ratios (5-10 percent), the time to raise 10°C decreased when compared to a negative control. For samples with high additive ratios (15-20 percent), the time increased compared to a negative control. These values were used to estimate thermal diffusivity using Equation 1, where α is thermal diffusivity (m^2/s), L is sample thickness (m), and t is time for temperature to rise 10°C (sec):

$$\alpha = \frac{L^2}{\pi^2 t} \quad (1)$$

The values indicate that low foam additive percentages result in increased thermal diffusivity of the cement, meaning heat transfers more quickly through it. High foam additive percentages, however, resulted in lower thermal diffusivity, meaning heat transfers more slowly through the samples. The calculated values are summarized in Table 2. The Cement All data sheet indicates the cured cement samples should have a density of 1.995 g/cc, which is slightly higher than our empirical value (1.975 g/cc) [11].

Table 2. Thermal Diffusivity Summary

Condition		*Thermal Diffusivity (mm^2/s)*
Negative Control		0.0440
CO_2-processed Foam	5% by vol.	0.0509
	10%	0.0458
	15%	0.0329
	20%	0.0298
N_2-processed Foam	5%	0.0571
	10%	0.0451
	15%	0.0236
	20%	0.0274

The foam is likely serving primarily to fill air pockets between cement particles; hence we see increase in thermal diffusivity. However, once a critical ratio is hit (somewhere between 10-15 percent additive ratio), it's likely that the foam particles are ubiquitous enough to interlock with each other creating additional air pockets. This observation accounts for both the reduced density and reduced thermal diffusivity when

compared to the negative control in higher loadings. Nevertheless, further comprehensive analysis is necessary to substantiate this hypothesis. The underlying mechanism, our findings suggest that the foam powder additive shows potential for applications focused on modifying the thermal properties of cement.

To assess feasibility in interior cement markets, we determine if/how the foam additive impacted paint adhesion to a cement surface. This test was performed using a standard tape peel test [12]. The tape peel test uses a rating system (0B-5B) to indicate the level of adhesion. All samples had either a 4B or 3B rating, indicating paint loss between 0 and 15 percent. While there is slight improvement from negative control in a few of the samples, there is no clear trend that our foam additive caused an impact (either positive or negative) on surface coating adhesion to the samples compared to a negative control. Our findings indicate there is little to no impact on surface coating adhesion due to addition of our powdered foam additive up to 20 percent, making it suitable for applications that requires both aesthetic and enhanced material performance.

For the possible use case as an additive to concrete in outdoor infrastructure (e.g., sidewalks or parking lots), the concrete would be exposed to salt for multiple months at a time. To assess the impact (if any) on salt corrosion resistance due to our foam additive, a salt spray test was performed according to an adaptation of ASTM Standard B117-11 focused on obtaining low-resolution qualitative results.

After exposure, samples with N_2-processed foam showed noticeable surface roughening at edges and corners compared to the control, indicating the beginnings of material loss, whereas samples with CO_2-processed foam showed only slight discoloration at the edges. This hints that the CO_2-processed powder may impart a tiny improvement in salt resistance, or at least does not increase salt susceptibility, whereas the N_2-processed powder might slightly weaken the cement matrix against salt. This result is preliminary, suggesting that if this application were pursued, focusing on the CO_2-processed foam additive would be preferable.

Rigid Foam Additive

We prepared samples using a commercially available rigid marine foam system with two parts (polyol and isocyanate). Samples were prepared by mixing foam powder with the polyol component in 5, 10, 20, and 40 percent by weight ratios for 3 minutes using a silicone mixing paddle attached to a drill to ensure homogeneity. This polyol mixture was then combined with the isocyanate component of the foam system in a 1:1 ratio, per manufacturer instructions. Once mixed, the foam was left in a fume hood for 24 hours to cure fully.

The average density of all rigid foams with additive ratios at or below 20 percent was lower than the control (Figure 7). This is extremely interesting, as adding solid filler to rigid foams often results in *increased* density. Qualitatively, these samples appear stiffer than the negative control. By adding our recycled foam powder, we achieved lower density rigid foam that is qualitatively stiffer. Typically, one expects a trade-off between density and mechanical properties, The interaction of soft and hard segments might reinforce the foam structure at low concentrations (below 20 percent). Our hypothesis is that the foam powder particles act as micro-bridges within the rigid foam matrix. More rigorous experimental work is currently being carried out.

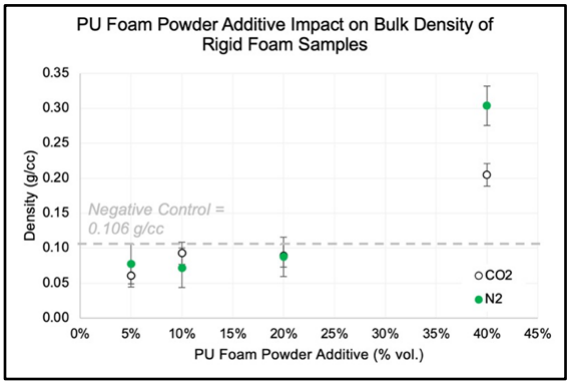

Figure 7: Powder Additive Impact on Rigid Foam Bulk Density. Image shows average densities of multiple rigid foam samples with powder foam additive ratios ranging from 5 to 40 percent by volume.

We also considered noise dampening impacts for multiple possible use cases (e.g., for automotive NVH applications, especially in electric vehicles). There are two major modes of noise conduction to consider: airborne noise and impact noise. Airborne noise includes things like rain, music, and sirens. Impact noise includes “road noise” and engine noise.

Typical industry standards to classify a material’s impact insulation class are based on ASTM Standards E492 and E1007. However, these are intended for assessing impact noises of floor-to-ceiling machinery;

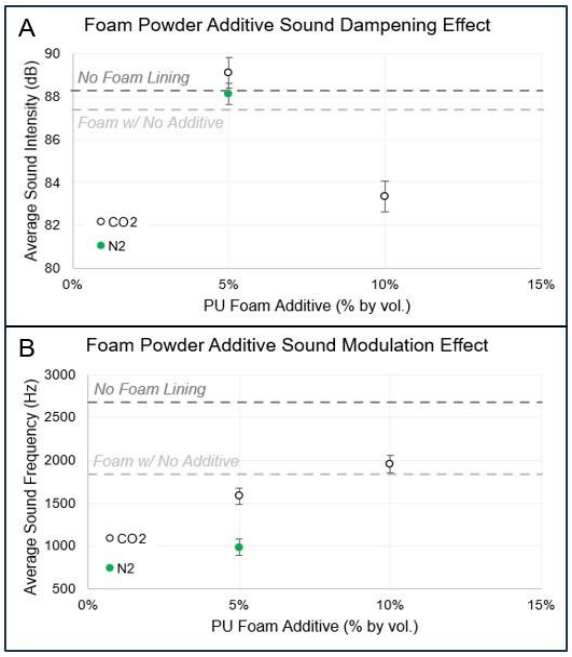

Figure 8: Dampening and Modulation Effects on Foam Samples with PU Powder Additive. (A) shows sound dampening effect on foam samples with additive. (B) shows sound frequency modulation effect on foam samples with additive.

as such, we modified these standards to be more relevant to our use case. We constructed an impact noise test rig using a ball bearing drop apparatus and a 3D-printed plastic box. We lined the box with foam and placed a microphone inside the box. A plastic pipe was lined up over the center of the lid, then a ball bearing was dropped through the pipe to impact the lid. The impact sound intensity and frequency were recorded by the microphone. This was repeated for a negative control, 5 percent by volume additive for both N_2- and CO_2-processed foam powder, and 10 percent by volume additive for CO_2-processed foam powder. Results for both intensity and frequency are shown in Figure 8.

Regarding sound intensity, neither sample with 5 percent additive ratio caused noticeable sound dampening. The sample with 10 percent additive ratio caused noticeable sound dampening, but only by a few decibels. However, all foam samples caused significant frequency modulation (reduction) compared to the unlined plastic box. This indicates that while dampening may not occur at drastic levels, highfrequency impact noises (which are often more noticeable or annoying) can be modulated to low frequencies. Current efforts are underway to better characterize this performance metric of rigid foam made with our additive, which could open pathways for product development in automotive and construction fields.

Compressed Foam Powder Sheets

We are also investigating whether the foam powder could be directly formed into a standalone material. Our goal was to pressure-sinter the powder into a solid sheet for possible use in filtration or direct paneling products.

Sheets were made by compressing 3 grams of powder at room temperature under compression forces of 2500, 5000, 10000, and 20000 psi with a dwell time of 15 seconds. One sample was made using CO_2-processed foam powder with a 20000-psi compressive force and a dwell time of 2 minutes.

For samples compressed under 2500 and 5000 psi, the sheets crumbled apart immediately after ejection. When the force was increased to 10- and 20 thousand psi, small pieces of the sheets stayed together after light pressure was applied, but these pieces had to be handled gently to avoid further damage. Generally, CO_2-processed sheets kept their structural integrity better than their N_2-processed counterparts, likely due to the surface functionalization introduced during grinding. Figure 9 shows one of the samples directly after compression and after the sheet broke into pieces. For compression into foam sheets to be successful, it's likely some binder, heat, or combination of both would be needed. This is likely worth exploring for future adjacency moves into applications such as filtration.

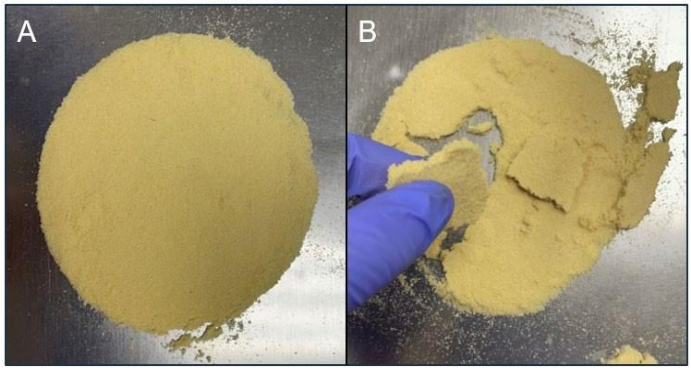

Figure 9: Compressed Foam Sheets**.** (A) shows sample immediately after compression. (B) shows sample after light pressure was applied by hand.

Discussion

Our characterization and applications results indicate we have developed a multiuse functional additive. There are promising paths forward to develop products exploiting the lightweighting, noise modulation, and thermal insulative properties of our foam additive. We have narrowed our initial target market focus on non-structural construction materials, primarily rigid foam paneling and interior cementitious mixtures. However, there are clear adjacency moves available for both the technology and chosen market. This indicates healthy room for growth and innovation when considering the commercial success of our additive.

Beyond the technical performance, it is important for our organization's mission to assess the environmental impacts of our process compared to conventional practices. To assess this, we conducted a preliminary life cycle impact assessment (LCIA) using openLCA software. Our analysis modeled 1 kg of processed foam, with electricity sourced from Duke Energy Progress East. We employed the TRACI 2.1 impact method for the assessment, using background data from the USLCI database and applying normalization and weighting via the US 2008 TRACI 2.1 set. To compare our process stands to traditional methods for foaming (i.e., making foam from virgin precursor materials), we compared our values to a cradle-to-grave analysis report from Franklin Associates [13]. This study evaluates the environmental impacts of producing polyether polyol only, meaning the isocyanate portion is not accounted for. A comparison to our flexible foam grinding method is shown in Table 3:

Table 3. Environmental Impact Comparison of Polyol Production vs. RoCo®'s Flexible Foam Processing

Factor	*Polyether Polyol Production*	*RoCo®'s Flexible Foam Processing*
Scope	Cradle-to-grave	Gate-to-gate (processing only)
Energy use	High (87.8 GJ/1,000 kg)	Very low (e.g., 0.15 kWh/kg)
Global warming potential	High (3,205 kg CO_2 eq/1,000 kg)	Negligible (0 kg CO_2 eq reported)
Solid waste	Significant (125 kg/1,000 kg)	Minimal (mostly packaging waste)
Water consumption	High (19,692 liters/1,000 kg)	None
Main impact drivers	Raw material synthesis (e.g., propylene oxide)	Electricity use
Software & databases	openLCA, USLCI, ecoinvent, GREET	openLCA, USLCI, TRACI 2.1

Interestingly, the results showed our process has no measurable environmental impact across all TRACI categories. This suggests that the grinding process is environmentally benign, especially when compared to the polyether polyol production, which is energy-intensive and emissions-heavy due to its reliance on fossil-based feedstocks and complex chemical synthesis. This contrast underscores the environmental benefit of recycling flexible foam through mechanical grinding (such as through our developed technology) rather than producing virgin polyol from petrochemicals. Thus, we can confidently conclude that flexible foam grinding is a low-impact process that effectively diverts waste into useful products.

Conclusions & Recommendations

We developed and demonstrated a mechanochemical process for converting flexible polyurethane (PU) into foam powder. This final design is readily scalable to accommodate industrial volumes required for successful market deployment. The design for the scaled version includes complete automation of loading, processing, and sieving, and is modular in virtually all aspects of the system to enable complete user control of the resultant foam powder.

The proprietary shear grinding technology developed over the course of this project shows incredible promise for scale and further development. We are currently able to achieve control of both the foam powder's particle size, resulting in a 10x reduction in bulk density from the recycled post-consumer chunks of foam-to-foam powder. While further characterization is still needed to fully understand the interactive effect on the foam powder between increased system temperature and type of gas perfused, we have shown definite proof that surface functionalization of the foam powder is occurring with our grinding process. We intentionally chose to scale back this characterization to focus on applications testing to find an ideal initial market.

When choosing an initial primary target market, we must balance the most interesting material characteristics we've uncovered thus far with the shortest route to a customer. We believe the best choice is to focus on use of our foam powder as an additive in rigid foam; from here, the most interesting characteristics caused by our foam additive are

noise modulation and increased rigidity at lower densities. Considering these, we believe the best primary target market is use as an additive in rigid foams used in construction (e.g., rigid foam slabs in building sidings, garage doors, front doors, etc.). Current efforts are ongoing to validate data described in this report, as well as to perform market validation for the selected target market. We are also working to build relationships with top customers, brand owners, and industry partners in the foam industry to ensure successful market entry for our product.

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