

PRELIMINARY STUDY OF ACOUSTIC AND PHYSICAL PROPERTIES OF FOAMED PAPER MILL SLUDGE PANELS

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Abstract. This preliminary study investigates the acoustic and related physical properties of panels manufactured from modified paper mill sludge (PMS) using a foaming technique. PMS is a by-product of the pulp and paper industry, presents significant disposal challenges but offers potential as a sustainable raw material for sound absorption applications. In this work, foamed panels were produced by introducing foaming agents in the sludge matrix to reduce density and enhance sound absorption. The panels were characterized for key physical properties, including density, porosity and sound absorption coefficient in frequency range from 200–5000 Hz. Additionally, Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) analysis were performed. The initial results indicate that the foaming process significantly improves porosity and reduces panel weight, contributing to enhanced acoustic absorption compared to non-foamed PMS panels. These findings suggest that new foamed paper mill sludge panels could serve as an eco-friendly alternative for sound absorption applications. The aim of this study was to evaluate the foaming influence on acoustic and related parameters of PMS panels.

Keywords: paper mill sludge, sound absorption, recycling, waste, foaming technique.

1. Introduction

Globally, more than 400 million tonnes of paper are produced every year. This is certainly a significant industrial process that also produces by-products. Paper mill sludge (PMS) is a by-product of paper production or recycling processes. PMS is produced during wastewater treatment processes. Estimates show that one tonne of paper produced, generates 4.3–40 kg of PMS (Turner et al., 2022). These rates vary due to the difference technology and efficiency of paper mills. Based on global paper production estimates, sludge generation could range from 1.72 million tonnes per year to 16 million tonnes per year (Turner et al., 2022). Although exact rates are unclear, it is important to realise the extent of sludge management as an important environmental and economic issue associated with paper production.

The composition of PMS varies depending on the treatment of wastewater and the efficiency of the mill. Organic contents consist mainly of cellulosic fibres, specifically cellulose, ranging from 28% to 68% (Duncan et al., 2020; Kang et al., 2010; Wang et al., 2010). PMS contains inorganic additives, the main component being calcium carbonate / CaCO_3 with a range

between 0.4% and 34%, used as a biochemical reaction buffering agent (Duncan et al., 2020). The content of calcite, kaolinite, talc and phyllosilicates content by mass is around 58% in sludges originating from primary clarification systems (Vegas et al., 2006). Due to dyeing processes, trace materials including sulphur (~2.33%) and other metals including aluminium, magnesium, silicon, sodium, manganese and molybdenum are found in PMS as well (Mohanapragash et al., 2025; Assis & Chirwa, 2021).

PMS can be processed for use as an absorbent for water pollution control (Likon et al., 2011), converted to agricultural additive such as biochar (Wang et al., 2021) (by pyrolysis) or compost (by vermicomposting) (Manyuchi et al., 2019). Energy recovery methods include the production of ethanol (Salameh et al., 2020) or gasification to produce syngas (Bonaldi et al., 2024). Studies show that PMS could be incorporated into construction materials such as ceramics (do Carmo et al., 2017), bricks (Goel et al., 2021), and asphalt (Chew et al., 2020).

PMS has also been studied as a material for sound absorption applications, often combined with other materials to enhance strength and sound absorption properties. For sound absorption applications, PMS was

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incorporated with other binding materials such as clay, slaked lime, and cement (Astrauskas et al., 2022; Astrauskas & Grubliauskas, 2021). The sound absorption of slaked lime and PMS composite sound absorption peaked at 1600 Hz and reached 0.3 (Astrauskas et al., 2022). PMS-clay composites demonstrated equal or superior absorption performance to commercial acoustic panels, registering an average sound absorption coefficient of 0.55 within the 250–1600 Hz frequency range (Astrauskas et al., 2021). Novel combinations, including PMS and waste tyre textile fibres and polyvinyl acetate, reached an average absorption coefficient of 0.50 (Ružickij et al., 2023). In those attempts to recycle paper sludge material, sound-absorbing PMS was used as a granular medium, which leads to limitations on how the material could be modified. This approach leads to a limitation of grain size and binding material properties. To tackle these limitations in this study foaming technique was tested on PMS.

Foaming technology is an advanced processing technique that introduces a controlled cellular structure into materials, optimising resource consumption while enhancing functional properties (Di Maio et al., 2015; Seo et al., 2012). By creating a lightweight, porous matrix foamed materials exhibit improved thermal and acoustic properties (Gutiérrez-Vázquez & Oñoro, 2008; Seo et al., 2012). Temperature and pressure are fundamental in governing pore size and distribution, directly affecting foam homogeneity (Potente et al., 2006). Material characteristics such as rheology, melt strength, and viscosity strongly influence bubble stabilisation and expansion during processing (Di Maio et al., 2015). The choice of foaming agents, chemical or physical—determines cell morphology and expansion ratios of cells, affecting mechanical and thermal performance (Gonçalves et al., 2024; Seo et al., 2012).

The foaming technique is a promising approach to recycle PMS as a sound-absorbing material. In this paper, a preliminary study of the foaming technique approach for PMS is presented. The aim of this paper was to test the physical and acoustic properties of foamed PMS.

The paper is organised as follows: In the Materials and methods section, the method of foaming technique and material characterization methods are presented. The Results and Discussion Section presents and discusses the main results of the study. In the Conclusions section, the main conclusions of the study are presented.

2. Materials and methods

In this section, the materials and methods used in this study are presented. Before the study, the PMS was stored air dry.

For this study 1–2 mm grain size PMS was used Figure 1.



Figure 1. Air dry PMS grains used for this study

2.1. Sample preparation method

The foaming process of PMS could be divided into four main technological steps: plasticization, blending, foaming, and drying. It is non-standard technique.

Plasticization is the process of making a material more flexible, softer, and easier to process or mould (Byun et al., 2013). For the plasticiser in this study, we used glycerol and tap water. 10% glycerol solution was used for plasticising. The total volume of solution was enough to sink the PMS. Glycerol was chosen as a plasticiser for PMS due to the high content of calcite and kaolinite. Glycerol is known to have plasticizing properties on those components of PMS (Agyei-Tuffour et al., 2021). PMS were left to plasticise for 7 days in room temperature.



Figure 2. PMS paste after blending

After the plasticization process, the PMS granules were blended using a blender (Model: Vitality G21; power: 1680 W; 32 000 rpm) until homogeneous mass was obtained. Figure 2 shows the PMS paste used for the foaming process.

As foaming agents, sodium bicarbonate (NaHCO_3) and citric acid ($\text{C}_6\text{H}_8\text{O}_7$) were used. The reaction between sodium bicarbonate and citric acid is a well-known acid-base reaction that produces carbon dioxide (CO_2), water (H_2O), and sodium citrate ($\text{Na}_3\text{C}_6\text{H}_5\text{O}_7$). The CO_2 produced within the matrix of the material helps to create foamed structure with pores and voids. The foaming process needs water, and

blended PMS has water due to the plasticization process. The foaming agents were mixed without water and then introduced into the PMS matrix. To check how foaming agents influence the parameters of acoustic and physical properties, 3 different foam samples were made. Mass percentages of 13%, 23%, and 37% were strategically selected to evaluate the transition from low-void to high-porosity composites. Specifically, the 13% loading serves as a baseline for high-strength applications, while the 37% loading explores the physical limits of weight reduction. This range allows for a comprehensive analysis of how foaming agent content dictates the balance between density reduction and other acoustic properties. Two control samples were used: one sample without foaming agents, another sample was picked up from previous study. The main parameters of the samples presented in Table 1.

Table 1. Samples used in this study

Sample title	Foaming agent	Binder	Source
Paste	0%	None	This study
Foam 13	13%	None	This study
Foam 23	23%	None	This study
Foam 37	37%	None	This study
Granular	None	PVA	(Ružickij et al., 2023)

The foam and paste samples were dried at 50 °C to ensure stable foaming process and drying of the samples. The drying process of the samples took 24 hours. In total 12 samples were prepared for this study, 3 samples for each configuration.

2.2. Method of determination true density and estimation of porosity of PMS samples

The true density of PMS was determined using an Anton Paar UltraPyc 5000 Foam (Figure 3). The method is based on the Archimedes principle of fluid displacement and Boyle's law of gas expansion to measure the true volume and density of the material. The measurements of true density were performed according to ISO 12154 (International Organization for Standardization, 2014). The nitrogen gas was used for pycnometric measurements.

For gas pycnometric measurements, a sample of known mass is put into a sample chamber of known volume, which is then sealed and pressurised with inert gas to a pre-defined value. The mass (m) of the samples was measured with an analytical scale with an accuracy of $0.1 \cdot 10^{-6}$ kg.

Finally, the open porosity (φ) of the PMS samples was calculated (Gomez et al., 2023) according to Eq. (1):

$$\varphi = \frac{\rho_t - \rho_b}{\rho_t},$$

where: φ – porosity of the material; ρ_b – bulk density; ρ_t – true density.

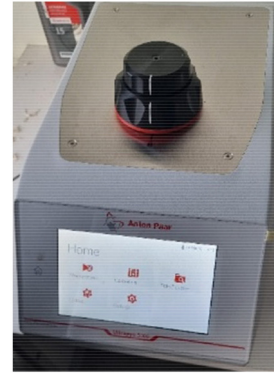


Figure 3. Gas pycnometer

The porosity and true density values show the effectiveness of the foaming technique in increasing the porosity of PMS and decreasing the density. Such parameters are extremely important for applications.

2.3. Method of scanning electron microscopy

The microstructural parameters of the PMS samples were examined using a Flex SEM 1000 scanning electron microscope (SEM) (Figure 4).

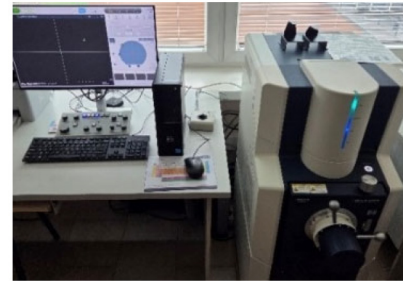


Figure 4. Scanning electron microscope used in the study

The samples were cut into small fragments to expose the fractured cross sections and the surface morphology. Before imaging, the samples were cleaned to remove loose particles and then mounted on an aluminium stub (80 mm diameter) using conductive carbon stickers. SEM observations were carried out under high vacuum conditions at an accelerating voltage of 5–10 kV using the secondary electron detection mode to capture detailed surface topography. The micrographs obtained were analysed to assess the quantity and the topography of the sample surface matrix.

2.4. Method of determination of normal incidence sound absorption coefficient

To obtain the sound absorption coefficient (SAC) (α) of PMS, the ISO 10534-2 standard method was used (International Organization for Standardization, 2001). Such a method was chosen due to the requirements for sample size compared with methods which can be performed in reverberant rooms. The impedance tube of 30 mm inner

diameter was used in the study. The three-microphone technique was implemented to obtain less noisy data. The measured frequency range was 150 to 6600 Hz. The experimental setup is shown in Figure 5. The white noise signal was used in this study, because it contains equal energy across frequency range allowing simultaneous measurement of acoustic properties of materials without performing multiple single-frequency tests. This approach significantly reduces measurement time while maintaining accuracy.

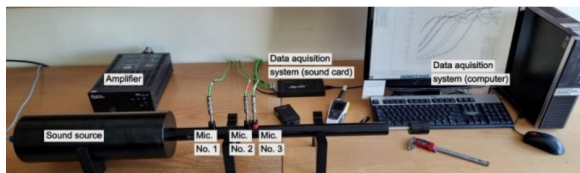


Figure 5. The impedance tube configuration for sound absorption measurements

The transfer function method was used with the three-microphone technique. In total 12 separate samples were tested for this study; 100 averages were done for each sound absorption measurement.

3. Results

In this section, the results are presented and the comparison with the previous study is made. First, the physical parameters of the materials are presented. Some of the properties of the material obtained using a gas pycnometer. Some of the parameters of previous study made by (Ružickij et al., 2023) are unknown. In Table 2 the main parameters of the materials are presented.

Table 2. Physical parameters of the PMS materials

Sample No.	Thickness, mm	Bulk density, kg/m ³	True density, kg/m ³	Porosity
1	8.1±0.3	767.4±29.6	1877.4±14.7	0.53±0.014
2	17.4±0.9	474.8±11.3	1874.7±27.2	0.74±0.008
3	18.5±0.3	376.5±26.4	1898.1±6.4	0.8±0.015
4	14.4±0.8	445.6±29.2	1876.1±9.0	0.76±0.14
5	18.2±0.9	626.0±24.8	–	–

In the table are presented sample thickness, bulk and true densities, and porosity. However, in the previous study the true density was not determined, therefore the porosity could not be compared. The results of the physical parameters show that foaming technique reduced the bulk density by up to 51% compared with PMS panel made with paste and up to 39% compared granular panel with the binder. The results showed that the foaming technique increased the porosity of the samples by up to 30%.

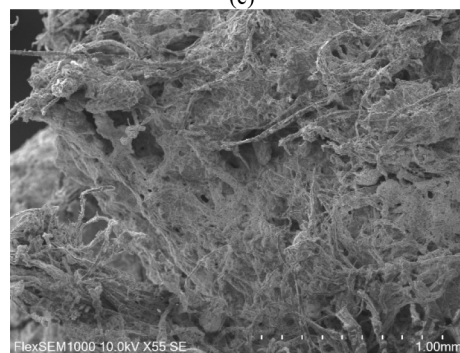
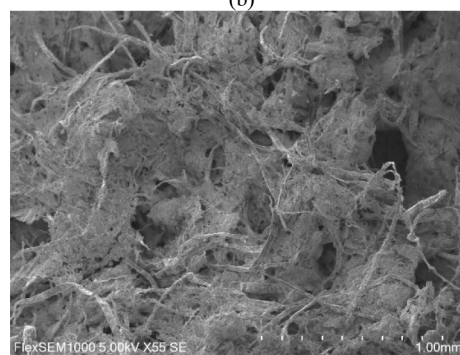
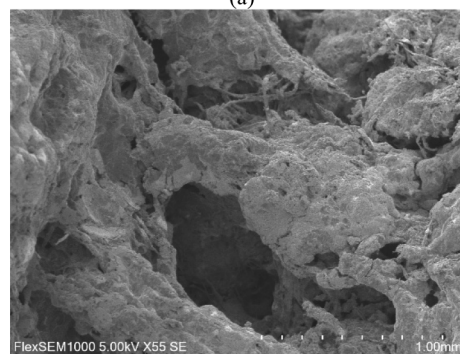
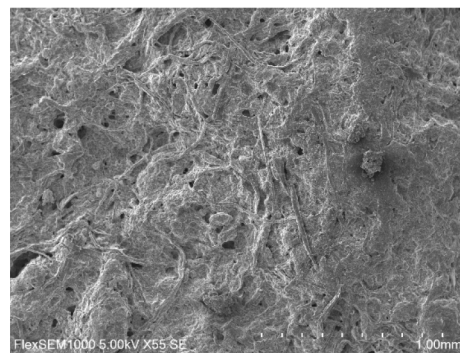


Figure 6. SEM micrographs of PMS samples: a – sample No. 1; b – sample No. 2; c – sample No. 3; d – sample No. 4

In Figure 6 SEM micrographs of SEM are presented. The analysis of the micrographs shows that the foaming process increases the number of voids and its volume. In Figure 6a a surface micrograph of the sample made from PMS paste is presented. The surface of the material is relatively smooth with small open pores

(diameter ≈ 0.06 mm). The fibres within the PMS matrix of the sample are connected to the surface. In Figure 6b much larger pores (diameter ≈ 0.5 mm) could be found, limited number of fibres are interconnecting and the material surface is rougher. In Figure 6c loose fibre-like particles was observed looser, but interconnecting. In Figure 6d the surface is similar compared with Figure 6c but it shows fewer voids. The assumption is that when used more foaming agent, too much gas was generated and PMS could not trap the CO_2 and the material collapsed within matrix; therefore, Figure 6d less voids are visible in that micrograph.

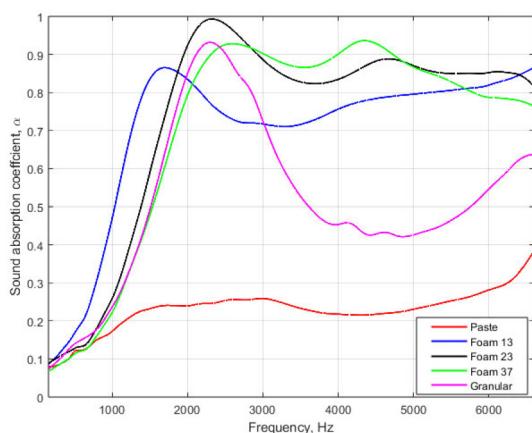


Figure 7. Sound absorption coefficient as function of frequency of PMS samples

In Figure 7 sound absorption coefficient as a function of frequency is presented. In the figure graph of the previous study (granular PMS) is also presented for comparison. The PMS without foaming made from paste (sample No. 1) showed low sound absorption compared to other samples and varied between 0.1 and 0.3. The samples showed higher sound absorption performance. The PMS samples prepared using the foaming technique showed a graph shape similar to other typical foams, without lowering sound absorption in the high frequency range. The peak sound absorption reached up to 0.98 at a frequency of 2500 Hz, and at higher frequencies varied 0.98–0.8 (Sample No. 3). In comparison, granular PMS material peaked 0.93, but at higher frequencies varied around 0.93–0.43. The SAC result increment of foamed PMS could be linked with an increase in the porosity of the materials. Such results show that the foaming technique has potential for PMS acoustic panel production.

Linear regression analysis was performed to test the influence on peak SAC of different non-acoustic parameters. Regression analysis showed that thickness did not have a significant effect on peak SAC ($R^2 = 0.09$; $p > 0.128$). The bulk density (Figure 8a) showed a significant effect on the maximum SAC ($R^2 = 0.9463$; $p = 0.000539$). The true density values did not show significant effect on SAC ($R^2 = 0.0946$; $p = 0.171$).

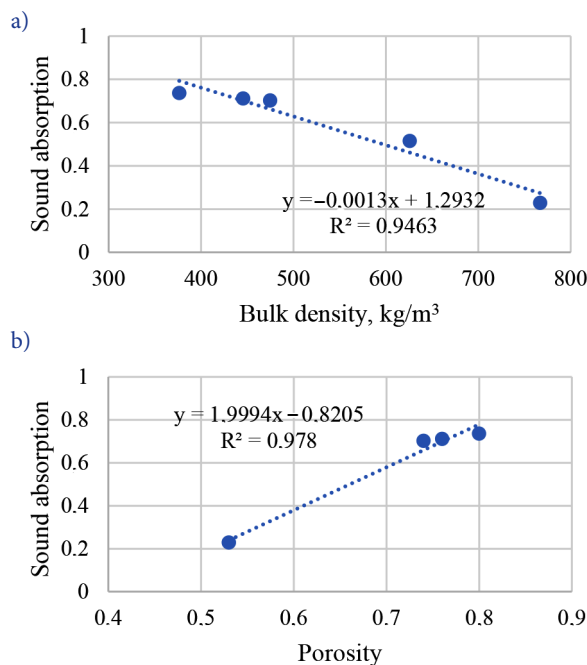


Figure 8. Sound absorption coefficient as function of frequency of PMS samples

The porosity values (Figure 8b) showed significant effect on SAC ($R^2 = 0.978$; $p = 0.0326$). Full regression analysis showed that the main parameters of the material that influence the peak sound absorption coefficient are the bulk density and porosity. Physically these two parameters are dependent on one another, as shown in this study. The regression analysis showed that porosity had the most significant effect on the peak SAC.

4. Conclusions

In this paper a new foaming technique method was proposed to produce acoustic panels using PMS as the raw material. The parameters of foamed PMS show good potential for future studies and applications.

The results showed that the bulk density decreased using the foaming technique. The decrease in bulk density reached up to 51% compared to the PMS paste sample and 39% compared with previously studied granular sample. Such findings show that such material would be more attractive to the building sector since it weighs less.

The foaming technique of sample production also helped increase sample porosity, which is a crucial material parameter for sound absorption performance. Samples prepared by the foaming technique showed 30% higher porosity values. The increase in voids in the foamed material was confirmed by SEM.

The sound absorption performance was also improved using foamed samples. Foam samples showed higher peak absorption (up to 0.98) and more stable sound absorption at higher frequencies with higher values (0.98–0.8).

This study shows only the potential of the foaming method. The study of foaming proportions to obtain optimal sound absorption and how foaming agents interact with PMS is still unknown. Future studies will address those unknown factors, but the results show that foamed PMS could be made into high-performance acoustic panels.

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