OPEN-CELL POROUS INORGANIC POLYMERS FOR SOUND ABSORPTION

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Introduction

One of the main environmental concerns in metal extraction is the co-production of metallurgical residues, such as sludges and slags.[1] In the case of Cu extraction, around 2.2 tons of Fe-rich slags are co-produced per ton of Cu,[2] which are transformed into more than 20 Mt/y. So far, these residues have been used in low added value applications as aggregates for roads and constructions.[3] One of the promising valorisation options is their use in the synthesis of a novel binder, *i.e.* inorganic polymers (IPs). Such binder could be used for multiple purposes, including the production of porous materials. For example, Kriskova *et al.*[4] synthesised porous IPs using a surface-active agent and a gas releasing agent, leading to morphologies with strength between 1.5 – 15.4 MPa and thermal conductivities between 0.156 and 0.348 W/m·K. Later on, Denissen *et al.*[5] investigated the influence of the SiO_2/Na_2O molar ratio of the activating solution, synthesis temperature and addition time of the gas releasing agent on the expansion kinetics of porous IPs. They found that when the SiO_2/Na_2O molar ratio decreased and when the synthesis temperature increased, the kinetics of expansion were accelerated. Nonetheless, the sound absorption properties of Fe-rich porous IPs have not been yet investigated. In fact, there is a lack of literature in the use of porous IPs as sound absorption barriers.[6] This study deals with porous inorganic polymers (IPs) synthesised by alkali activating a Fe-rich slag with concurrent foaming. Their sound absorption capacity is assessed and interpreted taking into account their porosity and thickness.

Materials and Methods

The production of the porous IPs involved mixing five components: Fe-rich slag, ground granulated blast furnace slag (GGBFS), alkaline activator, a surface active agent (surfactant) and a gas releasing agent. The Fe-rich slag and the GGBFS were mechanically blended in order to have a precursor with molar ratios of approximately Si/Al = 2.4 and (Si+Al)/(Fe+Ca) = 1.2. The alkaline activator was a mixture of sodium hydroxide, sodium silicate and water, to a final Si_2O/Na_2O molar ratio of 1.7 and an

H_2O/Na_2O ratio of 21.2. The surfactant was sodium oleate (purity 82%, Sigma-Aldrich) and the gas releasing agent was aluminium powder (purity 99.9%, AEE) with a particle size between 1 and 5 µm. The production of porous IPs can be summarised as follows: the slag blend was mixed with the alkaline activator and the surfactant, for 10 min, using a hand mixer. After this, the aluminium was added to the paste and it was mixed for another 2 min. The resulting material was then cast in a 15x15x15 cm^3 mould and cured for 24 h at 50°C. After the curing period, the samples were demoulded for sample preparation and characterisation. The compressive strength was measured on samples of 3x3x3 cm^3 by using an Instron 5985 testing device with a crosshead speed of 0.5 mm/min. The porosity of the samples was calculated using a SkyScan 1172 µ-CT from Bruker, with a medium camera, Al+Cu filter and pixel size of 8.9 µm. The samples for µ-CT analysis were cylinders of 1 cm height and approximately 8 mm in diameter. Finally, the sound absorption measurements were carried out by means of a Kundt Tube, in the frequency range of 100 to 4000 Hz, on samples of 4.6 cm in diameter and 1, 3, 5 and 7 cm in thickness. The noise reduction coefficient was calculated using the fourth middle octave-band frequencies (*i.e.* 250 Hz, 500 Hz, 1000 Hz and 2000 Hz).

Results

Compressive strength, density and porosity

As expected, the compressive strength and density of the synthesised porous IP showed to vary along with the porosity of the material (Table 1). The latter is mainly controlled by the percentage of gas releasing agent used in the mix. Furthermore, an increased porosity reduces the density of the material due to a higher total expansion, which is also accompanied by a lower compressive strength.

Table 1: Summary of the compressive strength, density and porosity results

Sample	Compressive strength MPa	Density (ρ) kg/m^3	Porosity (φ) %
0.10 wt% Al	3.4 ± 0.1	850	67
0.15 wt% Al	1.8 ± 0.1	600	75
0.20 wt% Al	1.0 ± 0.1	440	89

Sound absorption

The absorption behaviour at low and medium frequencies in highly permeable foams mounted in a Kundt tube is determined by two sources of standing wave behaviour: (i) interference between the incoming acoustic wave and the reflection at the rigid backing of the tube, (ii) interference between waves bouncing back and forth across

the thickness of the sample layer. In both cases, maximum absorption is reached when a standing wave velocity maximum is laying inside of the porous layer.

The total porosity of the samples appeared to have a significant influence on the maximum sound absorption coefficient reached in the mid and upper-mid frequency range, as the samples with higher porosity showed higher sound absorption within this region (Figure 1a). This can be explained by the lower resistivity of the sound wave travelling through the porous material with higher porosities. With increasing porosity, the speed of sound is expected to decrease, which explains why the increase in absorption sets in at lower frequencies as the porosity increases. Furthermore, an increase in the sample thickness showed to be favourable to reach higher sound absorption coefficients, especially at lower frequencies (Figure 1b): at 1 cm thickness, the sound absorption showed to reach a single absorption maximum at around 4000 Hz. At 3 and 5 cm thickness, two sound absorption maxima were located between 500-4000 Hz and for the samples with 7 cm in thickness, up to 3 sound absorption maximums were observed between 300-4000 Hz. This effect has also been reported in the literature, *e.g.* in the case of the study of Audrey T. J. L. & Ashby M. F[5], on metallic foams. They also showed that the thickness of the sample influences directly the sound absorption in the range of low frequencies (*i.e.* 100-2000 Hz), while the sound absorption at higher frequencies (*i.e.* ≥ 2000 Hz) is not influenced by the sample thickness.

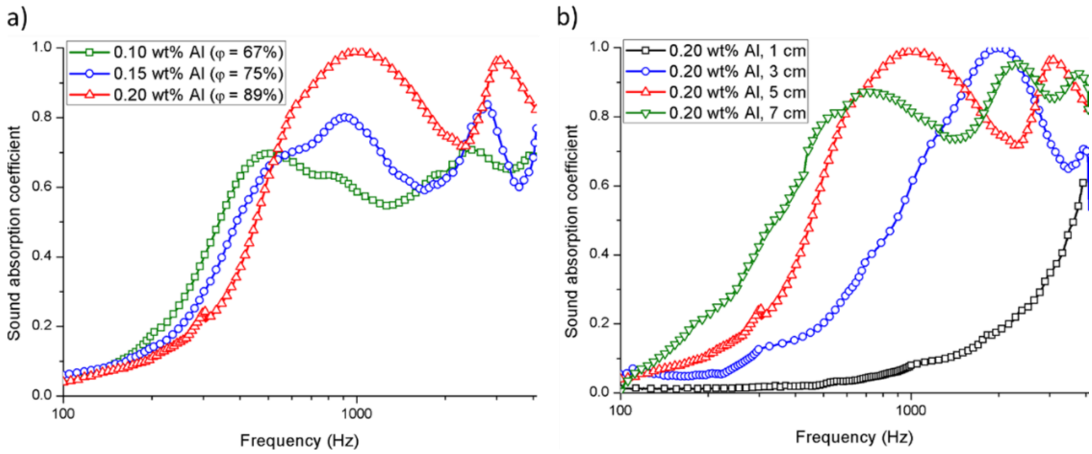

Figure 1: Sound absorption coefficient between 100 and 4000 Hz: a) porosity effect with constant thickness (5 cm) and b) sample thickness effect

The above-described behaviour is also visible in the noise reduction coefficient (NRC) of the different samples (Table 2). For every aluminium concentration, the NRC increases with increasing sample thickness. Furthermore, the NRC tends to increase with increasing aluminium concentration, due to the associated increase of porosity, which allows for more intensive interaction with incoming acoustic waves at high frequencies.

Table 2: Noise reduction coefficient (NRC) for all porous IPs

Sample	Porosity (φ) %	Noise reduction coefficient (NRC)
0.10 Al, 1 cm	67	0.15
0.10 Al, 3 cm		0.45
0.10 Al, 5 cm		0.55
0.10 Al, 7 cm		0.48
0.15 Al, 1 cm	75	0.19
0.15 Al, 3 cm		0.42
0.15 Al, 5 cm		0.57
0.15 Al, 7 cm		0.65
0.20 Al, 1 cm	89	0.06
0.20 Al, 3 cm		0.47
0.20 Al, 5 cm		0.63
0.20 Al, 7 cm		0.70

Conclusions

The sound absorption capacity of the porous IPs could be engineered, by modifications of their porosity as well as by a sufficiently large sample thickness, to reach high absorption coefficients in a broad range of frequencies. Increasing the porosity increases the absorption at high frequencies, at the expense of a decrease of absorption at low frequencies. Samples with higher porosity, however, have a lower compressive strength. Thus, depending on the envisaged application, the sound absorption needs to be seen as a function of other engineering properties and eventually design the processes accordingly.

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