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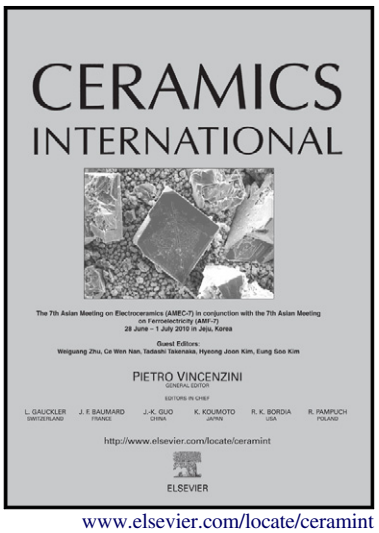

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A comparison between different foaming methods for the synthesis of light weight geopolymers

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Abstract

Foaming to reduce the density of geopolymeric materials is increasingly being reported in the literature as it has been shown to be effective in improving their insulating properties. However, there is no consistency in foaming methods and as such this study was performed to compare methods in order to better understand their effect on the properties of geopolymers. A surfactant and two chemical foaming agents (hydrogen peroxide and aluminium powder) were added to a fly ash based geopolymer matrix. Surfactant was also combined with each of the chemical foaming agents in order to stabilize the foam in the geopolymer matrix and to reduce coarse pores. The physical,

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mechanical and microstructural properties of the low density geopolymers are presented and the effects of the foaming agents' characteristics on the hardened product is discussed, as well as the relative merits of the different procedures to synthesise the foamed geopolymer. It was found that homogeneous microstructures with small pores can be obtained by adding surfactant and hydrogen peroxide. The combination of hydrogen peroxide (0.1 wt.%) and surfactant (1.0 wt.%) produced geopolymer foams with density and compressive strength values of 0.94 g/cm^3 and 4.6 MPa, respectively.

Keywords

Porosity B, Foaming agent, Surfactant, Geopolymers.

1. Introduction

Ordinary Portland cement, the most common cementitious building material, is responsible for a significant amount of global CO_2 emissions due to the decomposition of limestone and the combustion of fossil fuels during production. Geopolymer and other similar binders such as alkali activated materials (AAMs) have attracted a lot of attention [1-3] as suitable alternatives due to their significantly lower emissions during production [4]. An additional benefit of the use of geopolymer compared with OPC concrete is based on the possibility of using high-volume industrial waste in high-performance concretes, with a significant reduction in CO_2 emissions [5]. Geopolymer is a class of three-dimensional alumino-silicate materials [6]. Geopolymers are based on aluminosilicate units such as sialate [$-Si-O-Al-O$], sialate siloxo [$-Si-O-Al-O-Si-O$] or sialate disiloxo [$-Si-O-Al-O-Si-O-Si-O$] [6]. The polymerised materials contain tetrahedrally coordinated Al and Si, with charge balance of the Al tetrahedra being achieved by the presence of Na^+ or K^+ ions [7].

The weight of concrete represents a large proportion of dead load on a structure; the use of geopolymers of lower density is beneficial in terms of reduced structural load-bearing with further benefits of acoustic and thermal insulation [8-10]. However, mechanical strength relates strongly with density and low density geopolymers can

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exhibit unacceptably low strength [11]. Sufficient mechanical strengths can be achieved with the controlled addition of foaming agents in order to achieve an optimum density and pore structure.

Different foaming agents can be used to synthesise low density geopolymers. Surfactants are liquid admixtures that can be used to produce lightweight materials by entraining air during mixing. Another option is to use chemical products mixed into the geopolymer slurry which react with the alkali to generate gas which produces a foamed microstructure in the hardened material [12]. The addition of metals, such as zinc or aluminium, to the geopolymer paste generates hydrogen gas [13]. Metallic aluminium powder is commonly used and is very reactive in alkaline environments. Aluminate Al_2O^- and H_2 gas are liberated according to Eq. (1) [12]:

$$8Al + 2OH^- + 2H_2O \rightarrow 4Al_2O^- + 3H_2 \quad (1)$$

The reaction of metallic silicon present as an impurity in silicon carbides or silica fume also generates hydrogen gas when exposed to alkali [14,15]. Another class of chemical foaming agents is peroxides such as hydrogen peroxide and organic peroxides which react to evolve oxygen gas [13]. Bubbles of O_2 are trapped within the paste, expanding and increasing the volume. Hydrogen peroxide is thermodynamically unstable and can be easily decomposed to water and oxygen gas according to Eq. (2) and (3) [16]:

$$H_2O_2 + OH^- \rightarrow HO_2^- + H_2O; \quad (2)$$

$$HO_2^- + H_2O_2 \rightarrow H_2O + O_2 + OH^-. \quad (3)$$

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The synthesis of low density geopolymers using hydrogen peroxide is influenced by the optimization of the kinetics of peroxide decomposition with production of oxygen and the increase in viscosity of the geopolymer paste [17].

The synthesis of low density geopolymers represents a challenge and an optimized procedure should be investigated for each different foaming technique: small pore size and uniform pore distribution needs to be achieved and pore collapse should be avoided.

This paper presents a study on different foaming techniques to synthesise low density geopolymers. Physical and mechanical properties are reported as well as microstructural analysis of geopolymer samples. Varying concentrations of three foaming agents (surfactant, aluminium powder and hydrogen peroxide) were investigated in order to assess their influence on the final properties of low density geopolymers. Samples made with a combination of surfactant and chemical foaming agents were also studied in order to achieve a more homogeneous distribution of small pores.

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2. Materials and methods

2.1 Materials

Fly ash was sourced from the Eraring power station in New South Wales, Australia. Sodium aluminate solution was used as the alkali activator. Solutions were prepared by dissolving sodium hydroxide pellets from Univar Pty Ltd and sodium aluminate powder supplied by Sigma in deionised water. The solution was allowed to

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dissolve overnight at 70 ^{o}C and then used for synthesising geopolymers after 24 h. Aluminium powder with a particle size of 50 μm and a purity of 99.5% (product code AL006020, Goodfellow, U.K.) and hydrogen peroxide solution with 30% w/w supplied by Rowe Scientific were used as chemical foaming agents. Sika® Lightcrete 02 was used as the surfactant for foaming and is reported by the manufacturer to contain 40 wt.% solution of fatty acid, amide and sodium salt of C_{14}-C_{16} sulphonic acid in water.

2.2 *Geopolymer synthesis*

Geopolymers were synthesised with targeted compositional ratios of Si:Al=2.0, Na:Al=1.1 and a water content of 21 wt.%. Control samples were made by mixing the fly ash with the activating solution for 10 min.

Different procedures were used to add the foaming agents: the chemical foaming agents were added to the geopolymer slurry after the 10 min mixing period and mixed for a further 20 s at high RPM. Aluminium powder was added in concentration from 0.01 wt.% to 0.05 wt.% and the concentration of hydrogen peroxide was from 0.1 wt.% to 0.4 wt.%.

The surfactant (from 1.0 wt.% to 5.0 wt.%) was added to the geopolymer slurry after the initial 10 min mixing and mixed for a further 2 min with a whisk attachment at high RPM.

The concentration ranges are different for each foaming agent. The maximum concentration used was fixed at a level below the starting point of pore collapse phenomena that was determined for the geopolymer matrix used in this study.

Geopolymer mixed with surfactant and chemical foaming agents were synthesised with 1.0 wt.% of surfactant that was added after 5 min of mixing and the chemical

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foaming agents added after 10 min. Immediately after mixing, samples were poured into cylindrical moulds (50 mm diameter, 100 mm height), sealed and cured at 70 ^{o}C for 24 h.

2.3 Characterizations

The density of the samples was measured by dividing the dry mass by the volume. Cylindrical samples (50 mm diameter, 100 mm high) were used for density measurements. All reported results are an average of 4 different measurements.

Water absorption was calculated as the percent increase in weight of the specimens after exposure to water at ambient temperature until their complete saturation and/or sample weight does not vary more than 0.1%.

Pore size distribution measurements were carried out on all specimens by a mercury intrusion porosimeter (MIP, Carlo Erba 2000) equipped with a macropore unit (Model 120, Fison Instruments). Samples for porosimetry were cut by diamond saw to approximately 1 cm^3, dried under vacuum and kept under a P_2O_5 atmosphere in a vacuum dry box until testing. The MIP measurements were carried out using a contact angle of 141.3°, ~~and~~ a Hg surface tension of 480 dyne/cm and a pressure ranging from 0 to 200 MPa. Applying the Washburn [18] equation to calculate the pore dimension intruded by mercury at each pressure step, the pore radius ranging between 0.0035 μm and 33 μm can be detected. The suitability of MIP for pore size and pore size distribution is frequently debated [19-21], however its use in cement based materials is accepted [22-24], and it is becoming more common in the field of inorganic polymers [25-27].

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In the MIP measurements, during the Hg intrusion, the open pores, including the "ink-bottle" pores [19], are detected in the intrusion curve. At the end of the test, when Hg is extruded from the sample by lowering the pressure, a portion of the Hg remains in the "ink bottle" pores which allows the determination of the "ink-bottle" porosity. Thus, the total open porosity determined by MIP is the sum of two contributes: the "effective" porosity and the "ink-bottle" porosity [19].

Cylinders of 50 mm diameter and 100 mm height were prepared for mechanical testing. Samples were tested 7 days after synthesis. Compressive strength testing was conducted on a Lloyd universal tester EZ50 (UK). A load rate of 0.25 MPa/s was used to closely comply with ASTM C39 [~~19~~ 28]. The stated strength values are the average of results of 4 different measurements.

Scanning electron microscopy (SEM) was conducted on a NEON 40EsB (Zeiss, Germany) field emission SEM. Sample fragments were mounted onto aluminium stubs and out-gassed in a desiccator for 24 h. The samples were coated with a 5 nm layer of platinum prior to imaging.

Low magnification imaging was performed on samples using a Nikon SMZ 800 stereo microscope.

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3. Results

3.1 Un-foamed geopolymer

The control geopolymer paste exhibited a mean compressive strength of 21 MPa and a density of 1.72 g/cm^3. The un-foamed paste exhibited a few coarse pores caused by the normal entrainment of air in the mix prior to gel hardening (Fig. 1-A) and matrix

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characterised by values of water absorption of 22%. Fig. 1-B displays the microstructure of the fly ash geopolymer that was mostly composed of partially reacted fly ash particles bonded by the geopolymer gel.

The following sections outline the effects of the addition of various foaming agents to this formulation in order to synthesise a low density material (where the density is in the range between 0.7 and 1.2 g/cm^3).

3.2 Foaming geopolymers using surfactants

Varing amounts of the surfactant were added to try to achieve geopolymer paste densities of approximately 1-1.2 g/cm^3. The samples foamed with surfactant showed a homogeneous distribution of macro-pores in the range of 30-60 μm (Fig. 2).

MIP measurements show a clear increase in porosity and pore size distribution of the samples foamed with 2.0 wt.% compared with the 1.0 wt.% of surfactant (Fig. 3). For 3.0 wt.% surfactant, pore size distributions in the samples were intermediary between those achieved with 1.0 wt% and 2.0 wt.% of surfactant (Fig. 3). This trend was also shown by water absorption values with the highest value (approximately 50%) for the samples foamed with 2.0 wt.% of surfactant and values in the range of 36-40 % for increasing concentration of the foaming agent (Table 1).

Water absorption results can be influenced by the extent of large pores, which are not completely filled by water due to air present in the cavities. Of course, the more large pores that are present, the more water absorption measurement is underestimated, thus the values determined might reflect this aspect. However, MIP results confirm that open porosity (OP) increases with the surfactant content following this order: $OP_{2.0} > OP_{3.0} \approx OP_{4.0} \approx OP_{5.0} > OP_{1.0}$.

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Density was influenced by the concentration of surfactant added in the geopolymer mix too (Table 1). Density values are around 1.32 g/cm^3 for samples foamed adding 1.0 wt.% of surfactant to 1.18 g/cm^3 for ones in which 3.0 wt.% of surfactant was added. The lowest density value determined for the sample with 3.0 wt% can be ascribed to the large extent of ~~close porosity~~ porosity > 100 μm in the sample (Fig. 2). When the concentration of surfactant exceeded 3.0 wt.%, the density did not change significantly, thus confirming the occurrence of coalescence phenomena~~, which might promote the formation of closed pores~~.

Compressive strength values of geopolymers foamed with surfactant were in a range of 3.6 – 7.2 MPa (Fig. 4-A). As a general trend, increasing the surfactant content leads to a decrease in compressive strength, however when the concentration exceeded 3.0 wt.% no significant changes in compressive strength were recorded.

3.3 Foaming geopolymers using aluminium powder

Small concentrations of aluminium powder were added to the geopolymer pastes to create a foamed porous structure. It was found that increasing the aluminium powder concentration above 0.01 wt.% did not uniformly influence the physical and mechanical properties due to the high speed of the reaction and the increased tendency of pore collapse. For the 0.05 wt.% aluminium powder sample the reaction was very fast and most of the pores collapsed during casting and prior to gel hardening with a concomitant increase in density to 1.42 g/cm^3. All the other samples showed a density lower than 1.0 g/cm^3 (Table 2) and compressive strength values between 1.7 and 2.4 MPa (Fig. 4-B). Rickard et al. has also showed a decreasing trend of density and

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compressive strength values with increasing concentration of aluminium powder in geopolymer pastes [~~20~~29].

Optical images (Fig. 5) show that the pores formed by aluminium powder were generally coarse and not uniformly distributed at high additive concentrations. Most of the samples exhibited macro-pores from 500 μm to 3500 μm in diameter. Water absorption values of all the specimens were in the range of 24-27%. The reported values agree with the very large pores in the samples, which are not completely water saturated during the test~~, and with the presence of closed porosity~~.

Moreover, open pore size distributions show a similar trend for all the different samples foamed with aluminium powder and, regardless of the concentration of aluminium powder added, the dimension of most of the open pores was in the range between 0.4 and 3.0 μm (Fig. 6). It is likely that increasing the concentration of aluminium powder in the geopolymer mix did not produce extra foaming as there was a tendency for pore collapse prior to gel hardening.

3.4 Foaming using hydrogen peroxide

Four different concentrations of hydrogen peroxide were used as foaming agent. Increasing the concentration of the foaming agent resulted in a decrease in density (Table 3). When the concentration of hydrogen peroxide was increased to 0.4 wt.%, most of the pores collapsed and the density increased to 1.40 g/cm^3. Pham and Le reported a series of low density fly ash geopolymer mortar samples foamed with small concentrations of hydrogen peroxide with comparable properties to the ones in this study: density values were measured to be 0.52 - 1.41 g/cm^3, respectively [~~21~~30].

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The foamed samples with 0.1 wt.% of hydrogen peroxide showed a homogeneous distribution of macro-pores that were up to 200 μm in diameter (Figs. 7-A and 7-E). The further addition of hydrogen peroxide led to pores up to 8-10 mm (Fig. 7-B-C-D), still well distributed in the sample. Such behaviour is due to the coalescence of the pores with a resultant increase in pores size.

Increasing the concentration of hydrogen peroxide above 0.3 wt.%, caused even larger macro-pores and cross sections of the samples revealed that the bottom region was less foamed. This was likely caused by rising pores collapsing due to the low viscosity of the slurry prior to gel hardening and to the long setting time of the sodium aluminate activated geopolymers.

The water absorption did not increase significantly with increasing concentration of hydrogen peroxide (Table 3) and the values are similar to the ones obtained when aluminium powder was used as foaming agent. Hydrogen peroxide also promotes the formation of large pores thus affecting the water absorption values, as previously stated.

MIP measurements of geopolymers foamed with hydrogen peroxide are reported in Fig. 8. The total open porosity determined for these samples is higher than the ones determined when aluminium powder was used as a chemical foaming agent. Moreover, hydrogen peroxide, regardless its amount in the mix, promotes the formation of open pores with a very uniform distribution, being most of them in the range of 0.9-2 μm.

Increasing the concentration of hydrogen peroxide resulted in a decrease in compressive strength (Fig. 4-C): samples showed compressive strength in the range of 2.9 – 4.7 MPa. Pham and Le reported a series of low density fly ash geopolymer mortar samples foamed with small concentrations of hydrogen peroxide with comparable

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properties to the ones in this study: density and compressive strength values were measured to be 0.52 - 1.41 g/cm^3 and 3.0 - 5.2 MPa, respectively [21].

3.5 Combination of foaming agents

The addition of surfactants is known to stabilise foams [~~22~~31]. As such, a combination of surfactant and chemical foaming agents was trialled in an attempt to produce a more homogeneous pore structure by stabilising the pores generated by the chemical foaming. The samples with surfactant and aluminium powder showed an improved homogeneity of macro-pore size that was approximately 50 μm in diameter (Fig. 9) and a consequently significant increase in water absorption (Table 4) compared when only aluminium powder was used. ~~The increase in water absorption values is likely due to a better interconnectivity between the pores and size pores stabilization.~~

Fig. 10-A shows the pore size distribution of the samples foamed with the combination of aluminium powder and surfactant. MIP results confirms that the combination of the two agents support the formation of open porosities to a large extent.

For the investigated amounts of aluminium powders used in combination with the surfactant, the total open porosity as well as the open pore dimensions increase without collapse and coalescence phenomena, as previously determined.

The combination of the two foaming agents achieved a decrease in density to around 0.7 g/cm^3, indicating that the surfactant was effective in preventing pore collapse (Table 4). This low density is less than that recorded for the same concentrations of aluminium powder used by itself.

The addition of different concentrations of aluminium powder combined with the surfactant produced compressive strengths around 2 MPa (Fig. 11-A).

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The samples foamed with hydrogen peroxide and surfactant showed more homogeneity in the macro-pore size distribution compared to the samples foamed using hydrogen peroxide by itself (Fig. 12). Water absorption values increased with the increase in hydrogen peroxide concentration: with greater than 100% increase in water absorption for an increase of just 0.2 wt.% H_2O_2 (Table 5). In addition, a decrease in density values was measured when compared to samples with the same concentration of hydrogen peroxide only. The surfactant addition ~~enabled~~ formed a microstructure characterized by a large content of ~~interconnected and open~~ pores with dimension in the range 50-200 μm, similar to that was observed in the combined aluminium and surfactant samples.

MIP results highlight that large open pores with dimension ≥ 8 μm are present in great extent when hydrogen peroxide amount is added for 0.2 and 0.3 wt.%, whereas open pores with smaller dimensions are evident for 0.1 wt.% of chemical foaming agent (Fig. 10-B).

The combination of 1.0 wt.% of surfactant and hydrogen peroxide in the geopolymer paste exhibited densities in the range of 0.72- 0.94 g/cm^3 (Table 5) and compressive values in the range of 1.7 – 4.6 MPa (Fig. 11-B). Density and compressive strength clearly decrease with the increasing content of H_2O_2 in the mix.

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4. Discussion

Physical and mechanical properties of fly ash based geopolymers that were foamed using different methods and foaming agents have been presented. Authors are aware that the presented results are an average of a limited number of

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samples/measurements, thus the following comments and conclusions can be considered as a first insight into the main effects of the use of different expanding agents used to lower the density of geopolymers. More experiments are currently under investigation in order to better elucidate the observed phenomena.

Moreover, although MIP results have been compared with optical and SEM images analysis, the intrinsic imperfection of the mercury intrusion porosimeter technique must be taken into account. In the foamed samples the "ink-bottle" porosity ranges between 50-80 %, independent of the foaming agent and its concentration used in mixes, whereas for the un-foamed geopolymer it is 46 %. Such a large content of "ink-bottle" pores may be partly ascribed to the foaming, but mainly to the capillary pores formed during the geopolymerisation. Capillary pores in geopolymers differ from the capillary pores characteristic of Ordinary Portland cement [19-32]. In fly ash geopolymer systems, capillary pores have been ascribed by the retreat of fly ash particle surfaces as they dissolve after gelation and by the intrinsic porosity of the fly ash spheres (also known as cenospheres). This type of porosity is in the range of several micrometres up to 10 μm, and they appears disconnected and bounded by the gel appearing as "ink-bottle" pores, in scanning electron images [19-32].

Use of chemical foaming agents by themselves showed an increased tendency for pore collapse when compared with the use of surfactant. This, in part, was caused by the different composition of the gas that produces the foams. The surfactant enables the entrapment of air that is composed mainly of nitrogen and less permeable than O_2 and H_2 produced from the decomposition of hydrogen peroxide and aluminium powder, respectively [~~23~~33].

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To avoid pore collapse aluminium powder was added in small concentrations though the change in concentration was not found to influence the physical results in a uniform manner. Chemical foaming agents react at room temperature and the kinetics of the reaction is fast in high-alkaline conditions. This caused difficulties in controlling the pore size, as the foaming reaction started prior to casting into the moulds. Moreover, the presence of variable content of entrained air produced fluctuations in density values. This can be minimized by optimizing the mixing procedure. The exothermic mechanism of geopolymerization accelerates the chemical foaming reaction.

The procedure used in this study to synthesise foamed samples with surfactants did not achieve densities as low as 1.0 g/cm^3 although it has been recently reported that the use of gelcasting process produces lower densities [~~2~~434].

The combination of surfactant and chemical foaming agents produced a wider range of open pore sizes. The presence of the surfactant simplified the sample preparation because it stabilises the foam and reduces the tendency for pore collapse.

To increase the concentration of foaming agents in the geopolymer paste, it is necessary to have a more viscous mix that is less likely to be susceptible to coalescence of the pores and gas escape from the slurry. Alternatively a matrix with a faster setting time could be used [16]. In this study the geopolymer paste synthesised from fly ash had a relatively low viscosity and a long setting time due to sodium aluminate based activator.

The use of surfactant in the geopolymer paste produces a network of open-pores and increasing the concentration up to 2 wt.% in the mix was effective in increasing the ~~interconnectivity between the pores~~ water absorption (Table 1) and in extending the

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range of pore sizes (Fig. 3). The addition of 2.0 wt.% of surfactant in geopolymer produced suitable physical properties (Table 1).

Chemical foaming agents produced low density geopolymers characterised by coarse pores with the tendency to collapse at relatively high additive concentration. ~~Increasing the concentration of chemical foaming agents did not improve the interconnectivity of the pores.~~ Moreover, chemical foaming agents promote the formation of ~~closed porosity~~ more macropores (> 200 μm) than the surfactants, as demonstrated by the lower density values of the relevant geopolymers.

Fig. 13 compares the densities of the samples with the concentration of the various foaming agents. It can be observed in each case the density of the samples decreased before increasing again due to pore collapse when there was excessive foaming. A density of 0.80 g/cm^3 was achieved with 0.02 wt.% of aluminium powder. Hydrogen peroxide as a foaming agent allowed more control in changing the density in the matrix used in this study. In particular foamed samples with 0.3 wt.% of hydrogen peroxide exhibited the lowest density values of 0.91 g/cm^3 for this series.

Lower density and increased water absorption values were achieved in samples foamed with a combination of surfactant and chemical foaming agent (Table 4 and Table 5). This is likely due to the surfactant, which works as a foam stabilizer ~~creating a greater interconnectivity between the pores and~~ enabling the formation of a large content of pores ~~open porosity~~ with ~~a large range of~~ dimensions in the range 50-200 μm.

As a general trend the introduction of the foaming agent decreases the compressive strength of the expanded samples, however better control of mechanical strength that reduces with the increasing levels of foaming agent was determined when the surfactant and hydrogen peroxide were used by themselves and in combination.

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The addition of a small amount of aluminium powder resulted in a dramatic decrease in compressive strength and such behaviour was not mitigated when it was used in combination with the surfactant. Aluminium powder, due to its fast reactivity, promotes the formation of a high degree of ~~closed~~ porosity directly influencing mechanical strength and density regardless of the concentration used in the mix.

5. Conclusions

It was observed that the combination of surfactant and chemical foaming agents improved the synthesis of low density geopolymers. The best control of density and mechanical strength decrease was reached when hydrogen peroxide was used in combination with the surfactant. The use of the investigated chemical foaming agents when used by themselves promotes the formation of macro-size pores with dimension greater than 200 μm.

Foamed geopolymers have good potential in applications such as light weight building materials. However, pore size, pore distribution and the tendency of pore collapse must be controlled to achieve a homogenous network of pores.

Moreover, the side effects of the reactions products promoted by the addition of the different chemical foaming agents should be considered in a scale-up process, even if the chemical compounds are added in a very low concentration. Fore example the Al_2O^-, formed by the reaction of the aluminium powder with H_2O, could potentially take part in the geopolymerisation process, or the two mols of H_2O from each mol of added H_2O_2 might lower the pH of the reaction, thus reducing the geopolymerisation

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process. Finally, both the expanding reactions are exothermic, thus special attention should be focused on this matter in the reactor design.

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Captions:

Fig. 1. Optical (A) and SEM (B) images of the un-foamed geopolymer.

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Fig. 2. Images at two different magnifications of typical microstructure of geopolymer foamed using 3.0 wt.% of surfactant.

Fig. 3. Pore distributions of geopolymer samples foamed with surfactant. The graphs show the specific volumes of mercury intruded in the samples versus the diameters of the pores.

Fig. 4. Compressive strength and water absorption versus concentrations of foamed samples obtained by: (A) Surfactant, (B) Aluminium powder, (C) Hydrogen peroxide.

Fig. 5. Optical images of geopolymer sample cross sections foamed with different concentrations of aluminium powder: (A) 0.01 wt.%, (B) 0.02 wt.%, (C) 0.03 wt.%, (D) 0.05 wt.%.

Fig. 6. Pore distributions of geopolymer samples foamed with aluminium powder.

Fig. 7. Images of the cross section of a geopolymer sample foamed with different concentrations of hydrogen peroxide: (A and E) 0.1 wt.%, (B) 0.2 wt.%, (C) 0.3 wt.%, (D) 0.4 wt.%.

Fig. 8. Pore distributions of geopolymer samples foamed with hydrogen peroxide.

Fig. 9. Images of geopolymer cross sections foamed with 1.0 wt.% of surfactant and different concentrations of aluminium powder: (A and C) 0.02 wt.%, (B) 0.03 wt.%.

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Fig. 10. MIP measurements of geopolymer samples foamed with a combination of (A) aluminium powder and 1.0 wt.% of surfactant and (B) hydrogen peroxide and 1.0 wt.% of surfactant.

Fig. 11. Compressive strength and water absorption versus concentrations of the different foams: (A) Aluminium powder and surfactant, (B) Hydrogen peroxide and surfactant.

Fig. 12. Images of the cross section of geopolymer samples foamed with 1.0 wt.% of surfactant and different concentrations of hydrogen peroxide: (A) 0.1 wt.% , (B and D) 0.2 wt.%, (C) 0.3 wt.%.

Fig. 13. Comparing the changes in density of selected geopolymers using different concentrations of different foaming agents.

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Table 1. Physical properties of low-density geopolymers using surfactant (values in parentheses represent the standard deviation of the least significant number to the left).

Surfactant	Density (g/cm^3)	Water absorption
1.0	1.32 (2)	30 (1)
2.0	1.25 (2)	50 (1)
3.0	1.18 (2)	37 (1)
4.0	1.23 (2)	41 (1)
5.0	1.22 (3)	39 (2)

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Table 2. Physical properties of low-density geopolymers using aluminium powder. Properties of geopolymer foamed with 0.05 wt.% is not reported because the samples exhibited values of density too high for foams (values in parentheses represent the standard deviation of the least significant number to the left).

Al powder	Density	Macro-pore size	Water absorption
0.01	0.94 (3)	500-3500	24 (2)
0.02	0.80 (1)	500-3500	26 (2)
0.03	0.92 (2)	500-3500	27 (1)
0.05	1.42 (2)	1000-8000	-

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Table 3. Physical properties of low density geopolymers foamed with hydrogen peroxide. Properties for geopolymers foamed with 0.4 wt.% of hydrogen peroxide are not reported because foaming was not achieved at this concentration (values in parentheses represent the standard deviation of the least significant number to the left).

H_2O_2 (wt.%)	Density	Macro-pore size	Water absorption (%)
0.1	1.12 (2)	200-1500	25 (1)
0.2	1.04 (2)	200-1500	25 (1)
0.3	0.91 (1)	200-3000	30 (3)
0.4	1.40 (2)	500-5000	-

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Table 4. Physical properties of low density geopolymer using aluminium powder and surfactant (values in parentheses represent the standard deviation of the least significant number to the left).

Surfactant (wt.%)	Al powder (wt.%)	Density (g/cm^3)	Macro-pore size (μm)	Water absorption (%)
1.0	0.02	0.74 (2)	50-1000	54 (4)
1.0	0.03	0.73 (2)	50-1000	62 (1)

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Table 5. Physical properties of low density geopolymers foamed using a combination of hydrogen peroxide and surfactant (values in parentheses represent the standard deviation of the least significant number to the left).

Surfactant (wt.%)	H_2O_2 (wt.%)	Density (g/cm^3)	Macro-pore size (μm)	Water absorption (%)
1.0	0.1	0.94 (1)	50-1000	36 (1)
1.0	0.2	0.81 (2)	50-1000	61 (1)
1.0	0.3	0.72 (2)	50-1000	73 (1)

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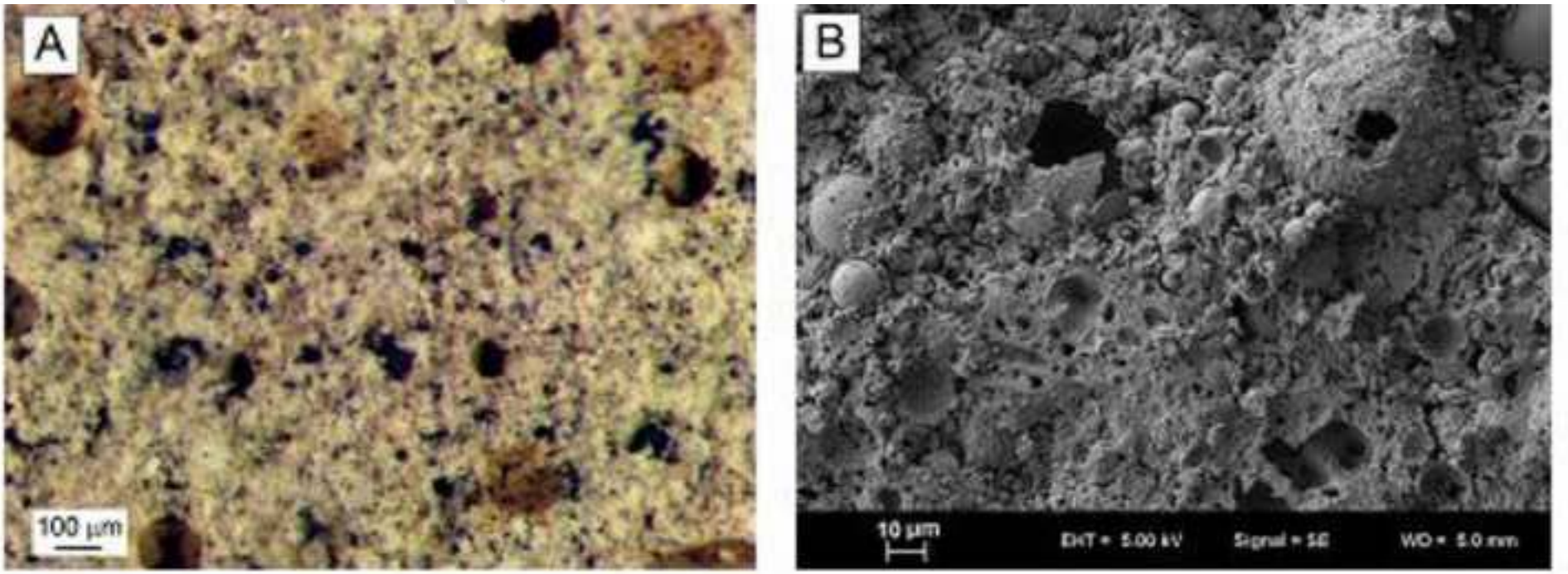
Figure1



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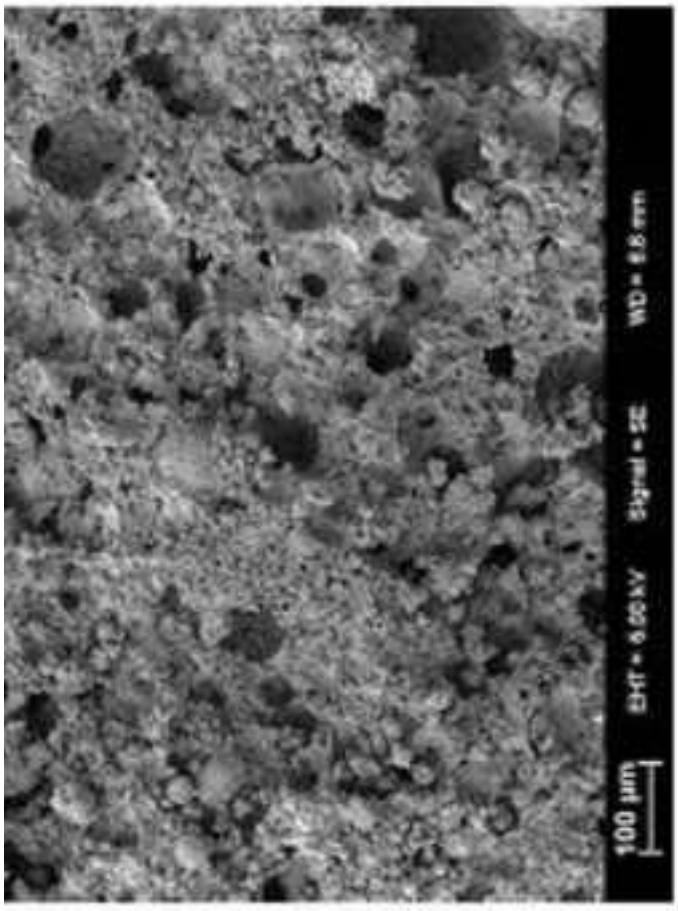


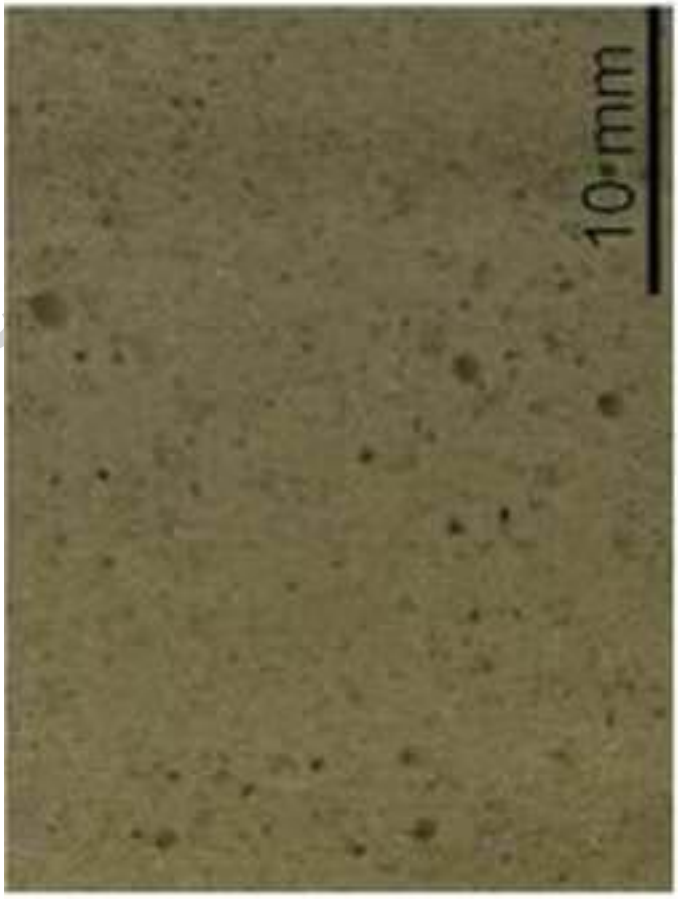


Figure2

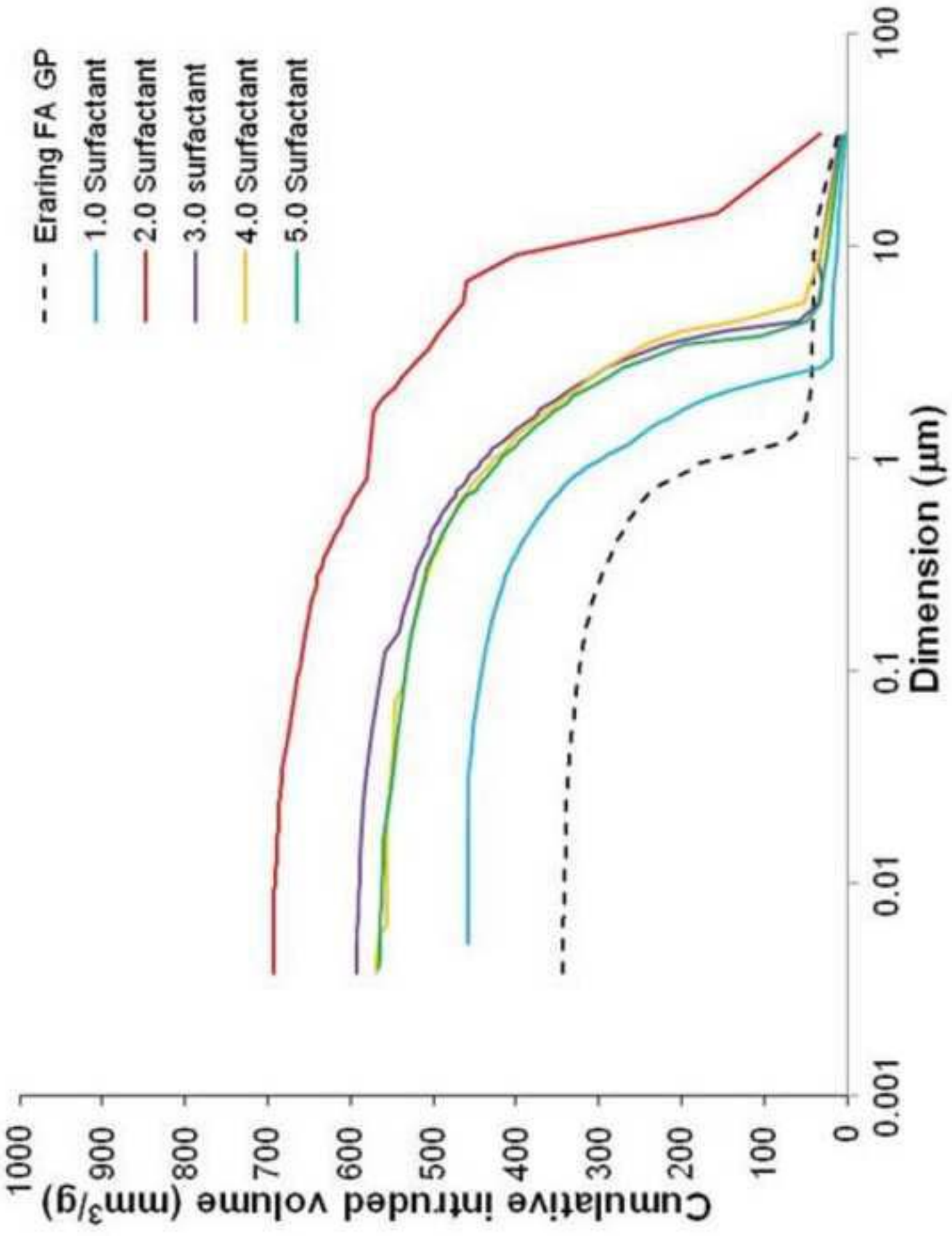
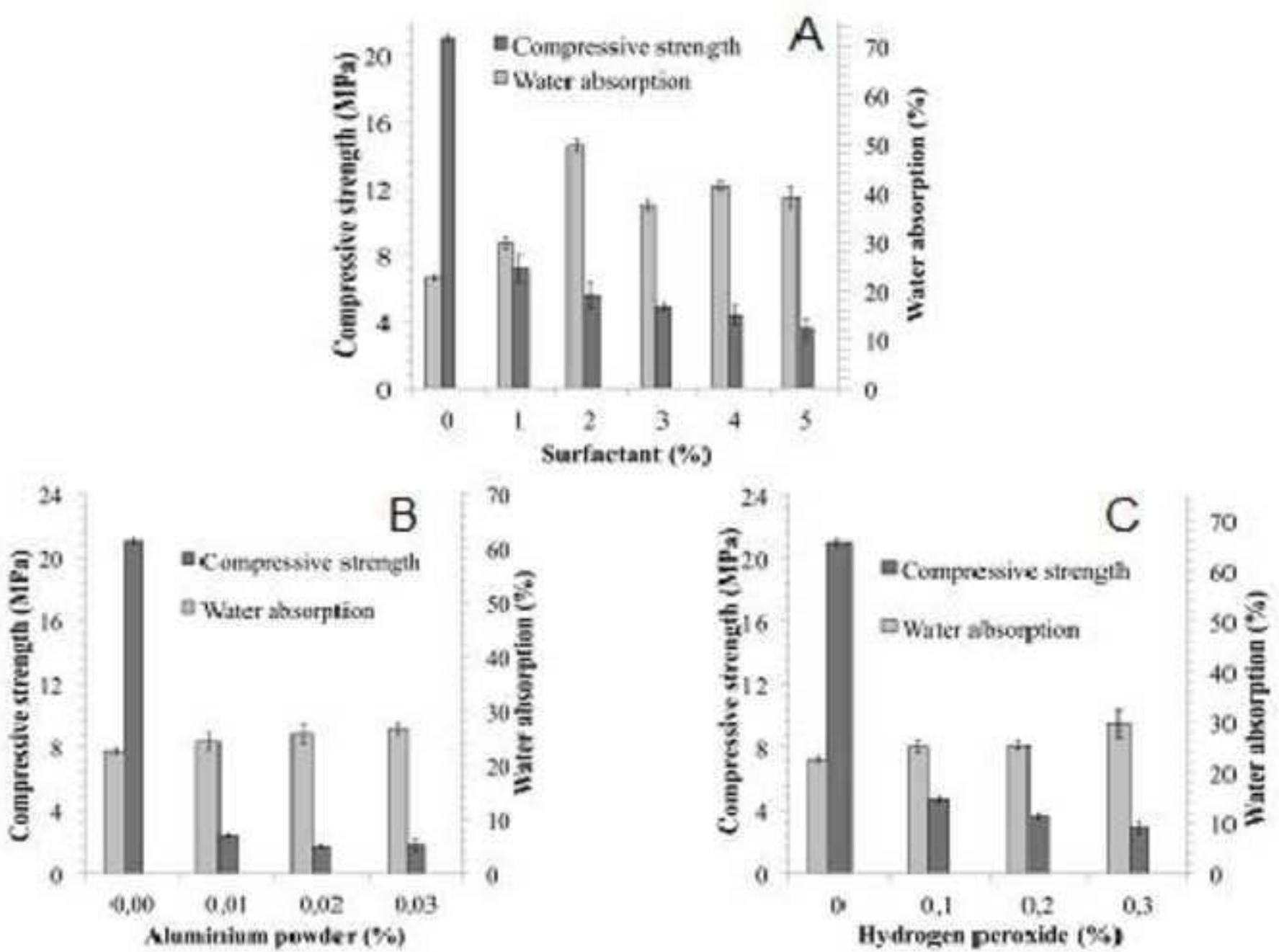

Eraring FA GP
1.0 Surfactant
2.0 Surfactant
3.0 surfactant
4.0 Surfactant
5.0 Surfactant
Cumulative intruded volume (mm³/g)
0
100
200
300
400
500
600
700
800
900
1000
0.001
0.01
0.1
1
10
100
Dimension (µm)

Figure3

Figure4



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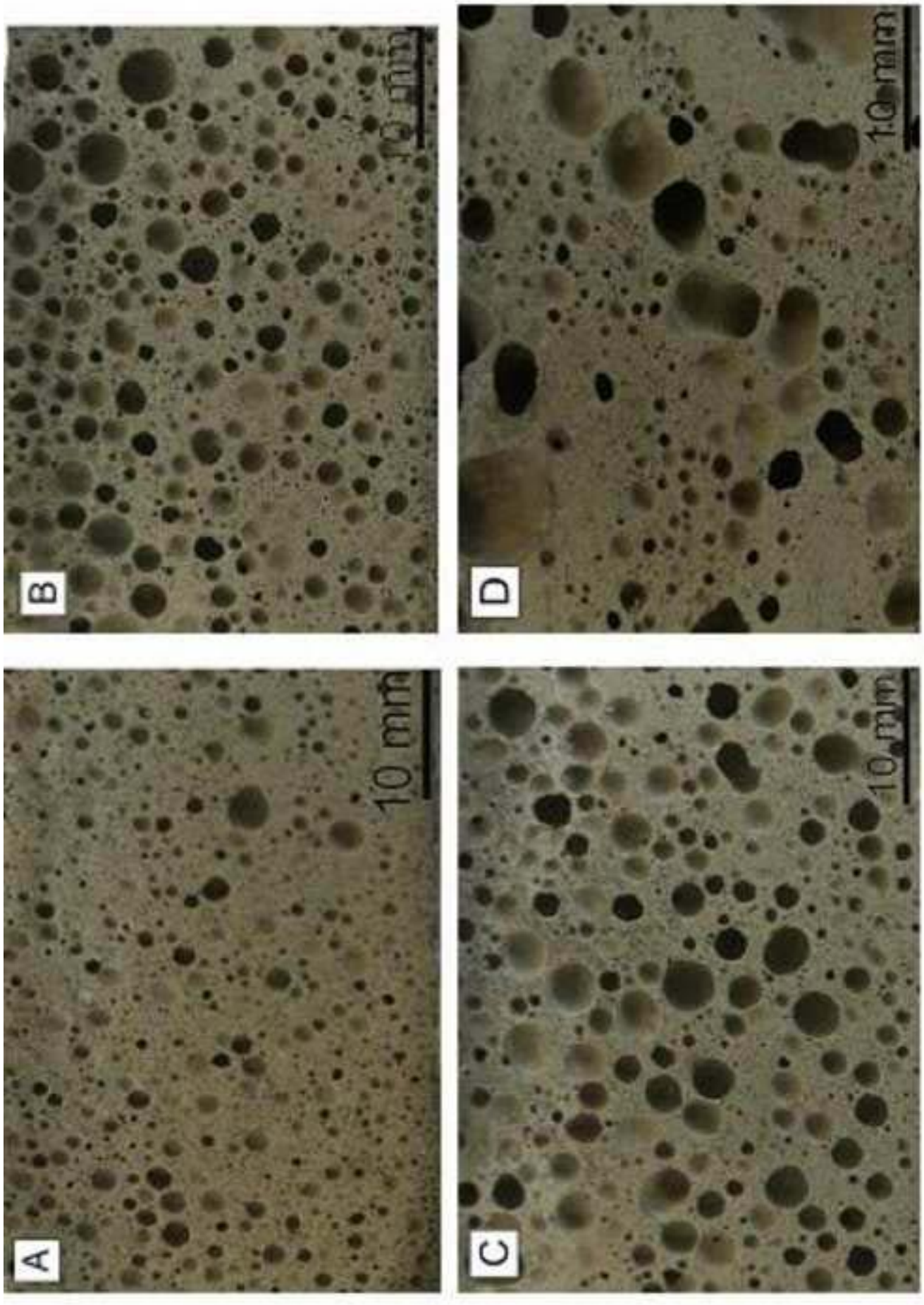

Figure5

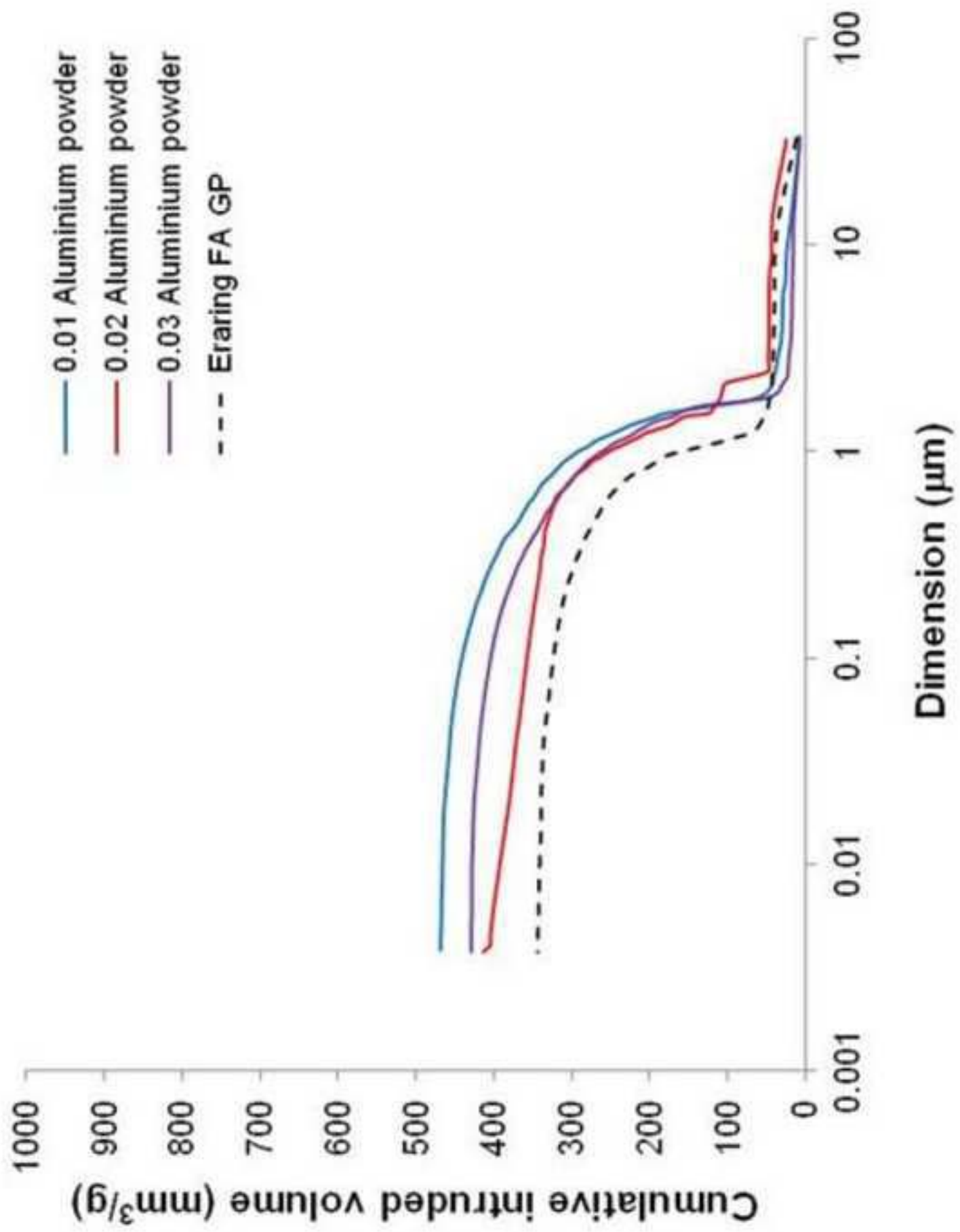
0.01 Aluminium powder
0.02 Aluminium powder
0.03 Aluminium powder
Eraring FA GP
Cumulative intruded volume (mm³/g)
1000
900
800
700
600
500
400
300
200
100
0
0.001
0.01
0.1
1
10
100
Dimension (µm)

Figure6

Figure7

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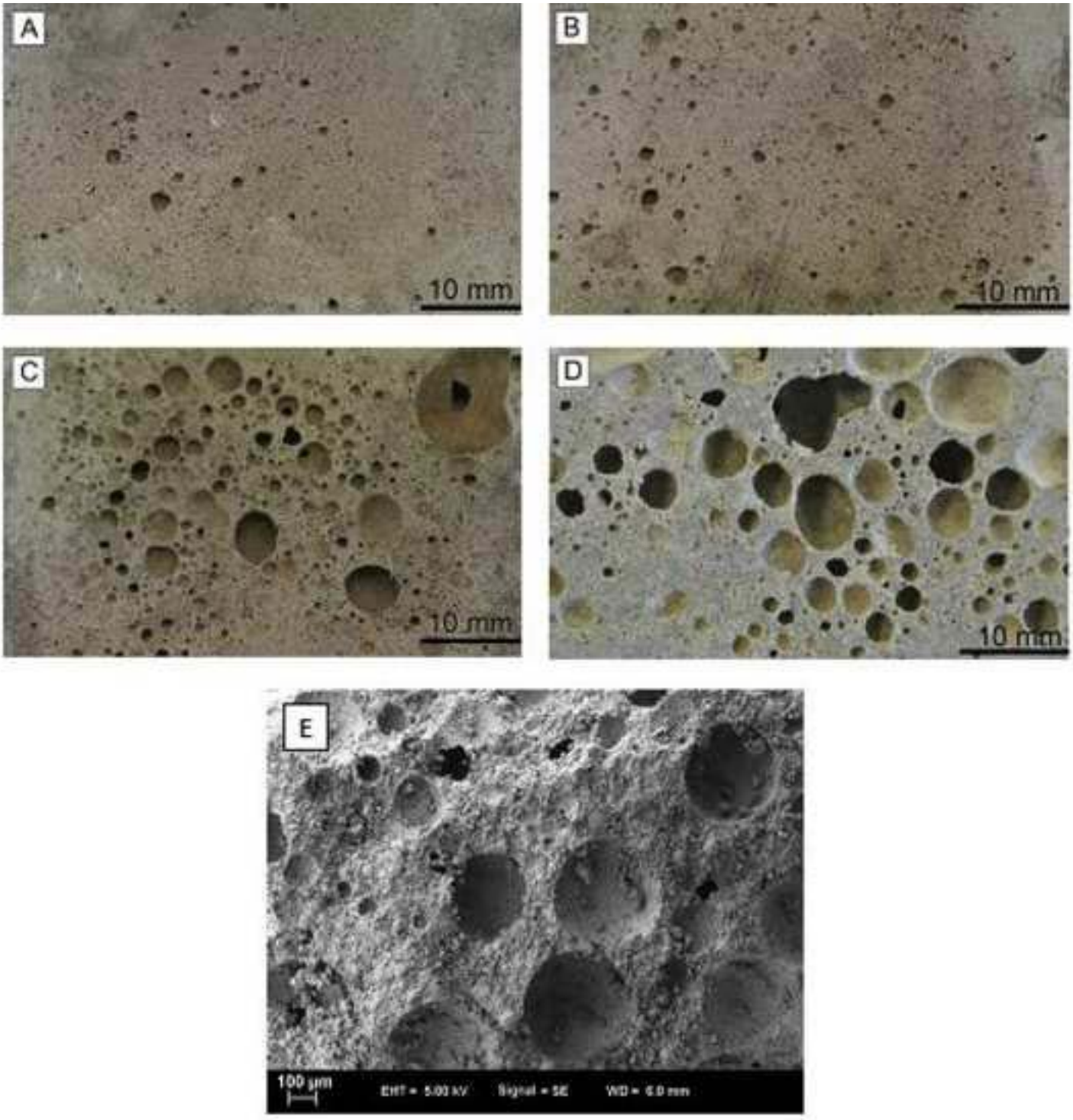

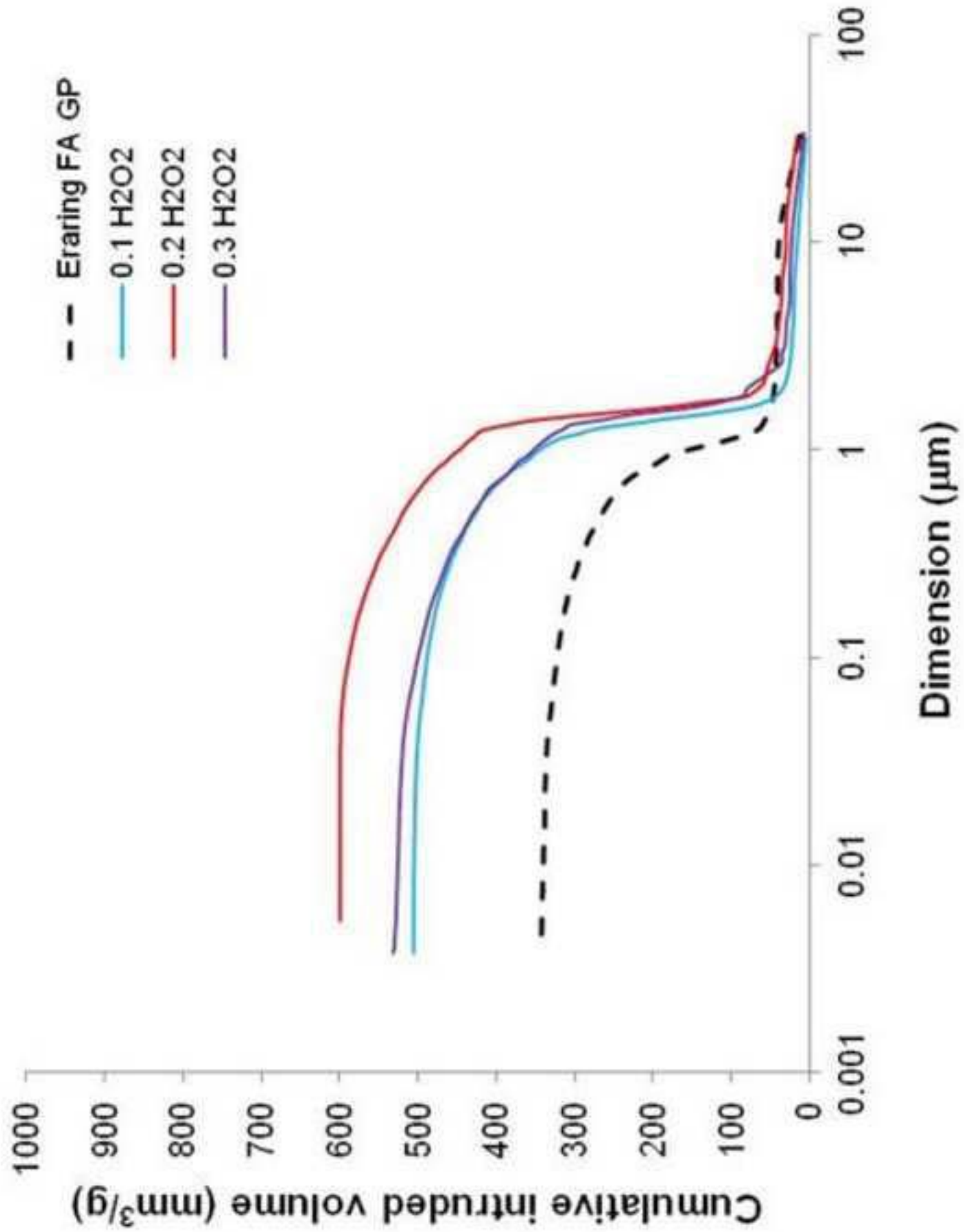
Eraring FA GP
0.1 H2O2
0.2 H2O2
0.3 H2O2
Cumulative intruded volume (mm³/g)
1000
900
800
700
600
500
400
300
200
100
0
0.001
0.01
0.1
1
10
100
Dimension (µm)

Figure8

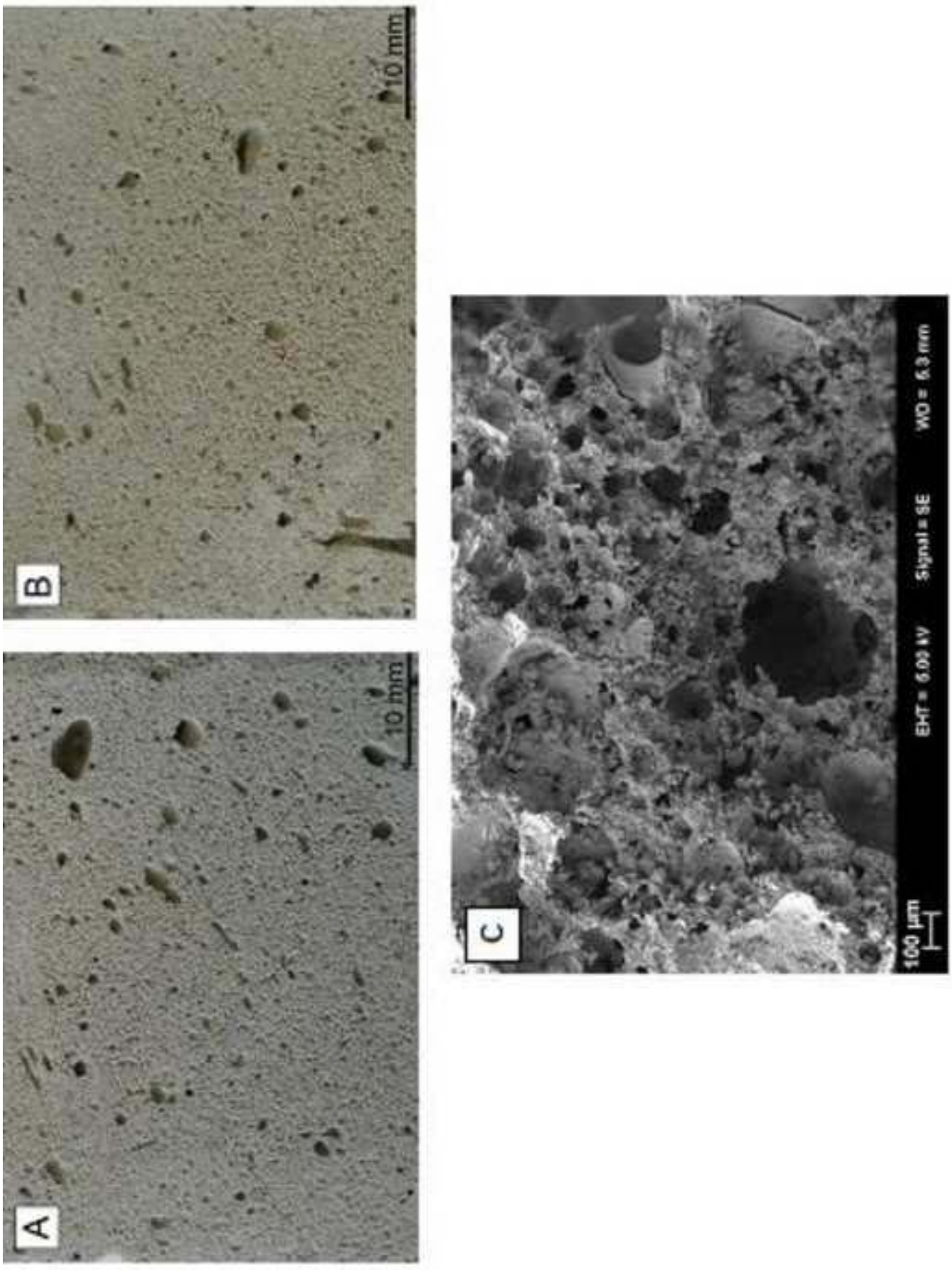

Figure9

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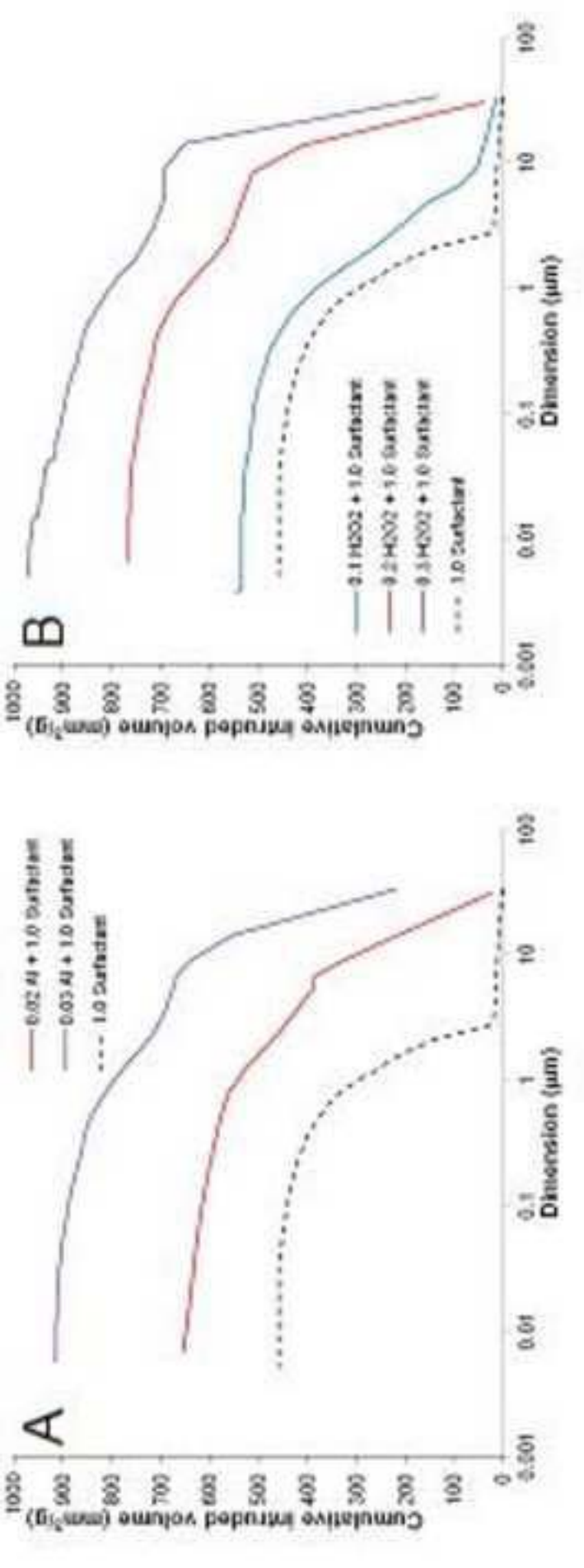

Figure10

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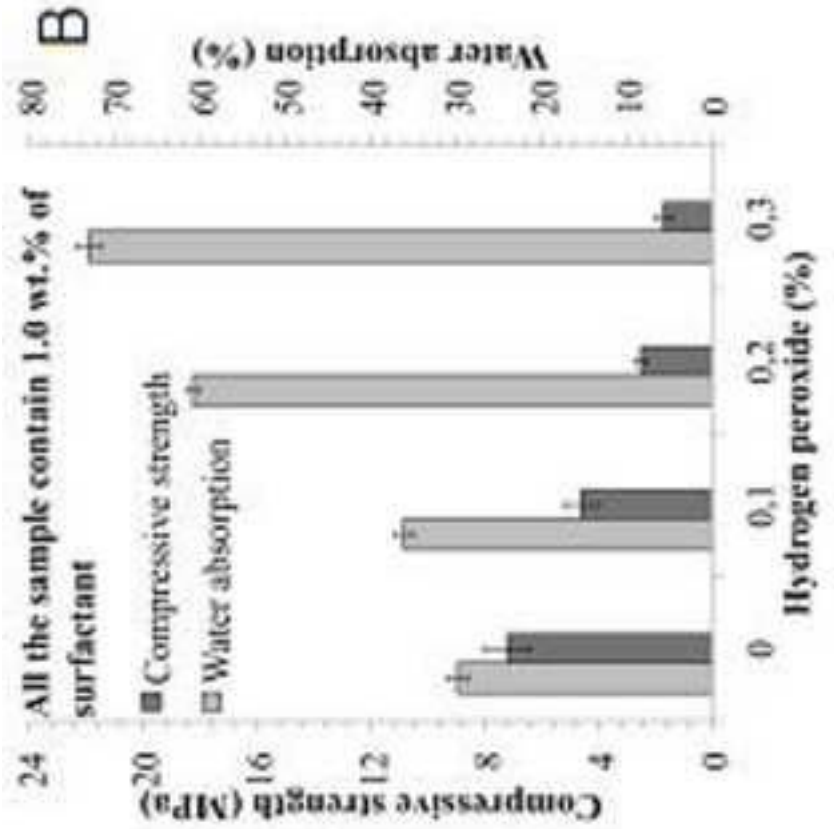
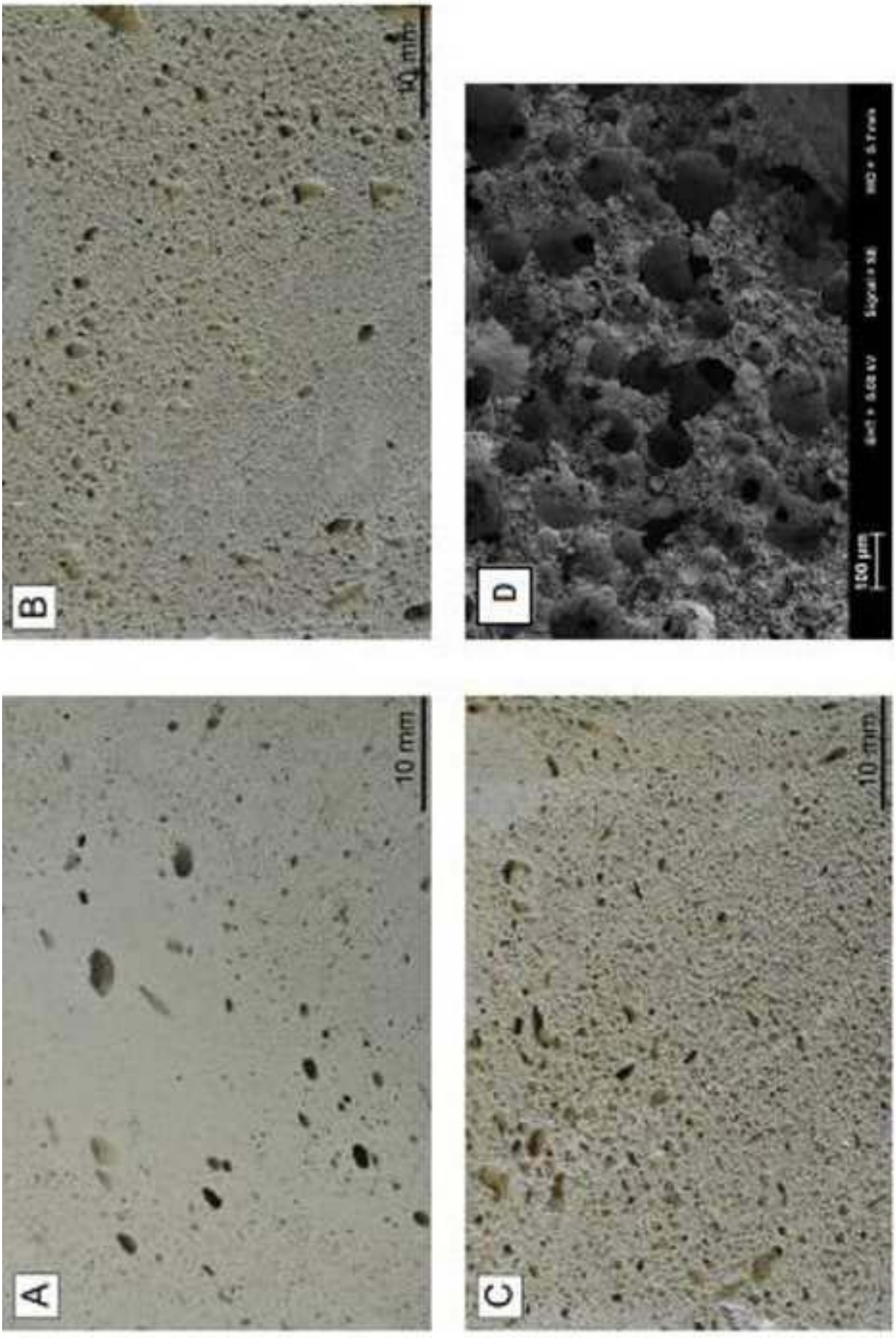
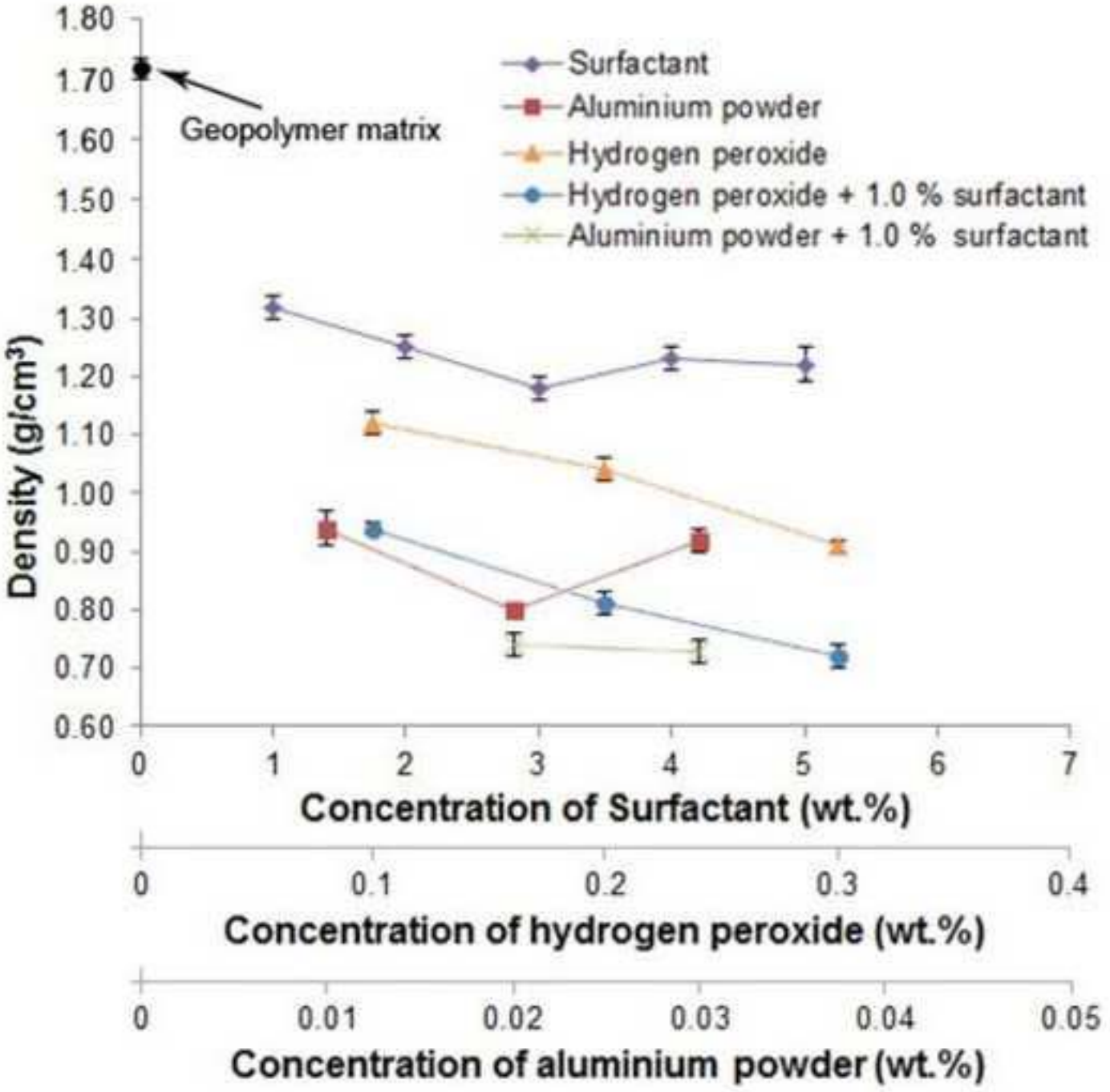


Figure



Figure

Figure



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