# ASSESSMENT OF COMPACTED-CEMENTITIOUS COMPOSITES AS POROUS RESTRICTORS FOR AEROSTATIC BEARINGS

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**ABSTRACT:** Cementitious composites reinforced with silica, silicon carbide or carbon micro-fibres (CMF) are designed, manufactured, characterised and tested as porous restrictor for aerostatic bearings. CMFs are residues obtained from the cutting process of carbon fibre reinforced polymers. Porosity, permeability, flexural strength and stiffness are quite relevant in the design of aerostatic porous bearings. A $3^1 4^1$ full factorial design (DoE) is carried out to identify the effects of particle inclusion and water-cement ratio (w/c) factors on the physical and mechanical properties of cementitious composites. Higher density material is achieved by adding silicon carbide. Higher porosity is obtained at 0.28 w/c level when silica and silicon carbide are used. CMFs are not effective under bending loads. Higher compressive strength is reached especially when silica particles are combined with 0.33 or 0.35 w/c. According to the permeability coefficient values the cementitious composites consisted of CMF (0.28 w/c), silica (0.30 w/c) or silicon carbide (0.30 w/c) inclusions are promising as porous restrictor, however CMF porous bearings achieved the lowest air gap variation under the tested working conditions.

**Keywords:** Porous bearings; physical and mechanical properties; cementitious composites

## 1. INTRODUCTION

Rolling-element bearings are commonly used due to their low cost and high rigidity, but they have limits of application when high speeds, low friction, repetitive movements, high temperatures or even special applications are required [1]. Friction is a particularly critical factor when smooth movement is required in ultra-precision machines [2]. Lubricating bearings can ensure smooth operation, but have high viscous frictional resistance, resulting in high-speed heating problems. In contrast, the aerostatic bearings use a thin layer of pressurized air to provide relative movement between surfaces with friction close to zero, avoiding problems related to friction, wear and lubrication. Aerostatic bearings have been a key component in the high-precision system, and the accuracy of movement and positioning of the nanometre scale has been achieved due to near-zero friction and low heat generation of gas lubrication [3].

The bearings are powered by an external air supply system. Pressurized air feeds an aperture between two bearing surfaces through a restrictor, being released in the surrounding environment from the outlet edges of the bearing gap to form a thin film acting as a lubricant. During work, motion surfaces do not come into contact, avoiding not only many conventional bearing problems, such as wear and friction, but also offering distinct merits for precise positioning [4]. The aerostatic bearings can be classified as 'orifice' or 'porous' media types. The porous restrictor provides a more homogeneous air pressure distribution, attributed to a large number of small constraints evenly distributed over the bearing surface [5].

Based on the open literature, the availability of porous materials that meet the requirements for an aerostatic bearing design is small. Alumina sintered [6], graphite [7], Portland cement [2] are examples of materials previously used in the manufacture of porous bearings. The use of cementitious composites as a restrictor for aerostatic thrust bearings was firstly investigated by Panzera *et al.* [2] revealing proper technical characteristics for such application, in addition to low cost and ease of manufacture. The material used as porous restrictor should provide not only high stiffness to withstand high air working pressure and minimise deflection, but also a uniform pore size and interconnectivity to ensure a homogeneous air pressure distribution and bearing stability [2, 5]. Typical properties for a single-layered porous bearing working at 5–15 μm air gap are: porosity level between 20% and 35%, permeability coefficient between $6.5 \times 10^{-16}$ and $8.4 \times 10^{-14}$ $m^2$ and flexural strength around 35 MPa [2, 5, 8].

Improvements in the physical and mechanical properties of a cementitious composite have been conducted towards the incorporation of fine and stiff particles/fibres [2, 5, 9–11], and mineral/chemical admixtures [9, 12, 13], in addition to alternative manufacturing techniques such as high uniaxial cold/hot pressing [14, 15], high temperature [13–15] and autoclaving [10, 16] cures.

The incorporation of fibres into cementitious products can improve the deformation characteristics of the cracks, increasing not only the toughness, impact, and tensile strength, but also eliminating the temperature and shrinkage cracks [17–19]. These benefits depend especially on the composition, size and shape of the fibres, which affect their bonding condition with the matrix phase [18]. The use of carbon micro-fibre (CMF) residues into polymer [10, 20] and cementitious [21] composites is quite recent in the literature, revealing significant improvements. Resin-coated CMFs wastes are generated during the process of cutting carbon fibre composites that can lead to environmental damage if discarded improperly [22]. Short chopped fibres (5–8 mm length) were added up to about 5% by volume in cementitious composites, leading to an increase in flexural strength without compromising compressive strength [23].

The microstructure of the cementitious products depends mainly on the cement hydration process, the characteristics of dispersive phases and the rheological behaviour of the system [24]. The effects of the water/cement ratio (w/c) on pore formation and mechanical strength of cementitious composites are well known in the literature [25], however, a small amount of information is available when uniaxial pressing is applied [14, 15, 26]. It is noteworthy that the open literature on materials for construction engineering does not contribute significantly to the present work, due to its particularity of application.

This work investigates the effect of three types of reinforcing particles (silica, silicon carbide, and carbon micro-fibre wastes-CMF) and four levels of w/c (0.28, 0.30, 0.33 and 0.35%) on the physical (bulk density, apparent porosity) and mechanical (dynamic modulus of elasticity, compressive strength, flexural strength and modulus) properties of compacted cementitious composites designed as porous restrictor for aerostatic bearings. In addition, a bench test for aerostatic bearings is used to evaluate the performance of such composites as porous restrictors.

## 2. EXPERIMENTAL

### 2.1 Materials

The cementitious composites are manufactured with Portland cement (ARI PLUS Type V, ASTM Type III) supplied by *Holcim (Brazil)* and three different reinforcement phases: silica particles (44-38 μm) sourced by *Moinhos Gerais* Company (Brazil), silicon carbide particles (10-20 μm) supplied by Saint-Gobain Company (Brazil) and carbon micro-fibre residues (CMF) obtained from the cutting process of carbon fibre epoxy composites, supplied by Carbontek S.L. Company (Spain).

## 2.2 Design of experiment (DoE)

A $3^1 4^1$ full factorial design (DoE) is performed to identify the effects of reinforcement type (silica, silicon carbide and CMF) and w/c (0.28, 0.30, 0.33 and 0.35) on the responses: apparent density, apparent porosity, compressive strength, flexural strength and modulus, and dynamic modulus. Table 1 shows the experimental conditions ($3^1 4^1 = 12$) and their respective factors and levels.

Table 1. Full factorial design ($3^1 4^1$)

| Conditions | Reinforcing phase | w/c |
|---|---|---|
| C1 | silica | 0.28 |
| C2 | silica | 0.30 |
| C3 | silica | 0.33 |
| C4 | silica | 0.35 |
| C5 | silicon carbide | 0.28 |
| C6 | silicon carbide | 0.30 |
| C7 | silicon carbide | 0.33 |
| C8 | silicon carbide | 0.35 |
| C9 | CMF | 0.28 |
| C10 | CMF | 0.30 |
| C11 | CMF | 0.33 |
| C12 | CMF | 0.35 |

The randomization procedure is adopted for the manufacturing and testing steps. This allows an arbitrary ordering of the experimental conditions, avoiding the effects of uncontrolled factors that may affect responses. Two replicates for each experimental condition are adopted in the experiment, with a minimum of 5 samples per condition and replicate. Replicate is performed to provide an estimate of the experimental error of the

individual response. Samples are manufactured in a controlled thermal environment at 23(±3)°C with a relative humidity of 55(±2)%, in order to avoid non-controlled factors, e.g. loss of water from cement paste, which can affect the responses. A means comparison test (Tukey) is used to identify groups that are statistically different from the others. Tukey test classifies the different means by groups of letters (A, B, etc), being those presented directly in the effect plots provided by DoE.

## 2.3 Manufacturing process

The cementitious composite is made by mixing the reinforcements and the cement phase considering a constant particle volume fraction of 43.73%. The particle volume fraction is converted to mass fraction to obtain the amounts by weight. The apparent density of each material was obtained by Brunauer-Emmett-Teller (BET) surface area analysis obtaining the following values: silica (2.69 g/cm$^3$), silicon carbide (3.25 g/cm$^3$), CMF (1.45 g/cm$^3$), Portland cement (2.98 g/cm$^3$). The phases are dry blended using a Pavitel I30-40 mixer for 3 minutes at low speed. The water is added with a subsequent mixing for 2 minutes at high speed.

Two metal moulds are used to fabricate cylindrical (27 mm in diameter and 70 mm in height) and prismatic (70 × 20 mm²) samples according to EN 12390-3 [27] and ASTM C1161 [28] protocols, respectively. A PVC tube is inserted into the cylindrical mould to be easily removed after compaction. In addition, a thin layer of release agent is spread on the inner and outer surfaces of the tubes. A constant mass of 110 g is uniaxially compacted at 30 MPa for 1 minute [26]. The samples are kept inside the PVC tubes, sealed by a plastic film to prevent loss of moisture, for 28 days at room temperature. After curing time, the samples are removed from the tubes and machined to obtain parallelism between the upper and lower surfaces according to [27]; the height is twice the diameter (~ ⌀27 mm × 54 mm). This sample is also used to perform the density, porosity and permeability tests. The prismatic samples follow the same manufacturing and curing procedure previous described. A mixture of 21 g per sample is used to obtain prismatic samples of 70 × 20 mm².

## 2.4 Response variables

### 2.4.1 Bulk density and apparent porosity

Bulk density and apparent porosity are measured by the Archimedes principle, according to [29], based on the mass of the sample under three conditions: $m_1$ - dry mass, $m_2$ –mass impregnated with water and $m_3$ - mass impregnated with water suspended. The dry mass ($m_1$) is obtained by drying the sample at 100(± 5)ºC until reaching the constant mass. The impregnated mass ($m_2$) is obtained after the samples are under vacuum with distilled water for 24 h. The mass $m_3$ is obtained by weighing the saturated sample suspended in water using a basket immerse in water. Bulk density is the quotient of its dry mass divided by the external volume ($m_2$ - $m_3$), including the pores. The apparent porosity is obtained by dividing the volume of open pores ($m_2$ - $m_1$) by its external volume ($m_2$ - $m_3$), being expressed as a percentage.

2.4.2. Oxygen permeability

An oxygen permeameter system is used to measure the permeability coefficient by differential gas pressure technique according to D´Arcy´s law:

$$\frac{dq}{dt} = \mathrm{K}.\frac{\Delta H.A}{L.\mu} \quad (1)$$

Where, dq/dt is gas flow rate ($m^3/s$); μ is the fluid viscosity ($N.s/m^2$); ΔH is the pressure gradient ($N/m^2$); A is the surface area of sample ($m^2$); L is the length of the solid (m). The sample is placed into a silicone cylinder and then inserted into a steel chamber, preventing any gas leakage that could interfere with the measurements made. The gas flow rate is measured using a bubble flowmeter as reported by Cabrera and Lynsdale [30].

2.4.3 Ultra-pulse velocity and dynamic modulus of elasticity

Young's dynamic modulus can be determined from a pulse of longitudinal vibrations produced by an electroacoustic transducer (Pundit). A 150 kHz transducer is used to measure the pulse transit time to traverse the sample in the longitudinal direction. Ultra-pulse velocity (UPV) can be calculated by diving the sample length by the time. The dynamic modulus of elasticity ($E_d$) is calculated based on Equation 2 [31], where μ is the Poisson's coefficient (0.20) [32], ρ is the density in $kg/m^3$ and UPV is the pulse velocity in km/s.

$$E_d = \rho.UPV^2\frac{(1+\mu)(1-2\mu)}{(1-\mu)} \quad (2)$$

2.4.4 Mechanical tests

Compression and three-point bending tests are performed using a 100 kN Shimadzu testing machine (AGX-Plus) at a crosshead speed of 0.5 mm/min. The dimensions of the samples and testing parameters followed the recommendations of BS EN 12390-3 [27] and ASTM C1161 [28].

2.4.5 Porous aerostatic bearing test

The cementitious composites are tested as porous aerostatic bearings using the bench (Figure 1A) developed by Resende *et al.* [33]. Air film thickness is measured at different loads using a precision pneumatic system consisted of three pneumatic transducers placed at 120º intervals around the bearing house. Electric-pneumatic transducers use compressed air to detect small variations of length with a resolution of 0.0001 mm. This measuring system, consisted of three measuring tools (pneumatic pen), an electric-pneumatic conditioner, an analogical-USB conditioner, a pressure regulator and a filtering system to eliminate particles and humidity, was designed and calibrated by Metrolog Company (Brazil). A precision granite table (Mitutoyo) was used as a reference surface for the bearing operation and air gap measurements.

Three different types of porous restrictor C2, C6 and C9 (see Figure 1B), are evaluated by varying the load capacity. The cementitious composite pad is cut from cylindrical samples with 50 mm in diameter and 8 mm thick to fit the metal rings as shown in Figure 1B. The cementitious composites are bonded to the metal rings using epoxy polymer. Thereafter, the restrictor pad is subjected to the grinding process using a tungsten carbide grinding wheel without coolant to prevent pore blockage.

[Figure 1]

## 3. RESULTS AND DISCUSSIONS

3.1 X-ray diffraction analysis

The X-ray diffraction (XRD) patterns of cementitious composites made with silica and silicon carbide are shown in Figure 2. The patterns for all cementitious composites show the presence of hydrated cement products, such as:

- Portlandite (p, $Ca(OH)_2$) with the main peaks at 2θ 17.97º, 28.75 º and 34.13º (PDF #44-1481 and [34],
- Calcium silicate hydrate (CSH) peak at 2θ 29.4 º (PDF #33-306 and [34]),

- Calcite (C, $CaCO_3$) with peaks at 2θ 23.07°, 29.43°, 39.44° and 47.15° (PDF #5-586 and 28 [34]).

In addition, it can be observed the presence of unhydrated products such as:

- Alite (a, $C_3S$) (PDF #49-442 [34]),
- Larnite (L, β-$C_2S$) (PDF #33-302 [34]).

Quartz (Q, $SiO_2$) with main peaks at 2θ 20.92°, 26.65°, 50.17° and 60.02° (PDF #46-1045 [34]) is observed for silica cementitious composites (C1 to C4), see FigureA, and for silicon carbide (SiC) (main peaks at, PDF #49-1428, #49-1431) cementitious composites (C5 to C8), FigureB. Due to the amorphous morphology of resin-coated CMF (C9 to C12), only sharp Bragg peaks for portlandite are shown, which preclude a more detailed analysis for the others cementitious phases.

[Figure 2]

3.2 Scanning electron microscopy

Scanning electron microscopy (SEM) analysis is conducted to identify the morphology of the particles. Figure 3 (A, B and C) shows the SEM images of the silica, silicon carbide and CMF, respectively, with magnification of 500×. Silica and silicon carbide particles (Figure 3A, B) reveal an angular shape due to their mineral comminution process; meanwhile, CMFs (Figure 3C) have a large aspect ratio (height/diameter) due to the intrinsic characteristics of carbon fibre. The spherical particles shown in Figure 3C, along with CMFs, are oxides of the ink, since the residues come from the cutting process of the carbon fibre fins.

[Figure 3]

3.3 Physical and mechanical properties

Table 2 shows the means and standard deviation values, considering replicates 1 and 2, for physical and mechanical properties.

Table *3* shows the statistical analysis, i.e., the ANOVA results considering a level of significance of 5% (p-value ≤ 0.05). The p-values less than 0.05 indicate that the main or the interaction of the factors significantly affect the response, these being underlined in Table 3. When an interaction effect is significant, we can analyse the factors together rather than the individual ones.

The adjusted R-squared and the p-values for Anderson-Darling test ranged from 96.60% to 99.84% and from 0.119 to 0.888, respectively, revealing well fitted models and normal distribution data, with p-values greater than 0.05, which validates the DoE analysis.

Table 2. Results for physical and mechanical properties of cementitious composites.

| | Replicate | $\rho_b$ *g/cm³* | $p_{ap}$ *%* | $E_d$ *GPa* | *UPV* *m/s* | $\sigma_c$ *MPa* | $\sigma_f$ *MPa* | *Ef* *GPa* |
|---|---|---|---|---|---|---|---|---|
| Sil28 | R1 | 2.03±0.03 | 24.45±0.01 | 21.79±1.62 | 3.42±0.23 | 56.27±5.98 | 14.82±1.38 | 3.60 ±0.59 |
| | R2 | 2.02±0.02 | 25.25±0.01 | 21.33±1.94 | 3.31±0.26 | 51.93±4.25 | 15.00±0.39 | 3.89 ± 0.30 |
| Sil30 | R1 | 2.01±0.01 | 19.74±0.04 | 18.01±0.99 | 3.68±0.16 | 62.09±7.13 | 14.16±2.23 | 3.70 ±0.62 |
| | R2 | 2.03±0.01 | 19.96±0.01 | 19.32±0.68 | 3.21±0.80 | 61.81±7.01 | 13.58±2.11 | 3.74 ± 0.65 |
| Sil33 | R1 | 2.10±0.02 | 14.71±1.02 | 18.80±1.25 | 3.09±0.16 | 72.36±7.74 | 13.60±1.50 | 5.26 ±0.60 |
| | R2 | 2.10±0.07 | 14.91±0.07 | 18.97±1.44 | 3.16±0.12 | 72.06±3.36 | 13.90±2.18 | 5.39± 0.61 |
| Sil35 | R1 | 2.08±0.02 | 12.06±0.01 | 17.71±0.64 | 3.02±0.11 | 66.16±5.99 | 14.07±2.49 | 5.62 ±0.12 |
| | R2 | 2.09±0.01 | 12.88±0.01 | 18.72±1.25 | 3.12±0.12 | 68.26±2.06 | 14.37±2.07 | 5.56± 0.25 |
| SC28 | R1 | 2.48±0.01 | 27.95±1.61 | 33.72±2.82 | 3.93±0.02 | 30.93±8.12 | 16.38±2.49 | 3.11 ± 0.32 |
| | R2 | 2.48±0.01 | 28.26±3.64 | 33.26±1.45 | 3.88±0.09 | 33.45±5.02 | 16.33±2.32 | 3.13 ± 0.31 |
| SC30 | R1 | 2.42±0.02 | 25.60±0.44 | 32.27±0.22 | 4.14±0.17 | 36.18±7.15 | 14.56±1.46 | 4.38 ± 0.42 |
| | R2 | 2.45±0.01 | 24.98±9.67 | 33.26±1.84 | 4.17±0.09 | 38.55±4.28 | 14.17±0.86 | 4.27 ± 0.25 |
| SC33 | R1 | 2.75±0.02 | 20.65±0.05 | 30.79±3.34 | 4.26±0.20 | 28.74±5.51 | 14.53±1.18 | 5.49 ± 1.06 |
| | R2 | 2.74±0.03 | 21.09±0.02 | 31.68±3.20 | 4.13±0.22 | 30.98±3.66 | 14.22±0.67 | 5.27 ± 0.27 |
| SC35 | R1 | 2.65±0.05 | 19.65±0.02 | 27.25±1.57 | 3.77±0.09 | 27.18±4.16 | 14.56±1.10 | 5.69 ± 0.39 |
| | R2 | 2.71±0.02 | 20.06±0.01 | 26.37±7.42 | 3.65±0.48 | 31.19±2.38 | 14.78±0.59 | 4.36 ± 0.42 |
| RC28 | R1 | 2.16±0.01 | 20.15±0.02 | 14.35±0.02 | 2.87±0.01 | 48.79±0.68 | 9.34±0.82 | 3.31 ± 0.82 |
| | R2 | 2.14±0.02 | 20.34±5.89 | 14.34±0.01 | 2.88±0.04 | 45.72±10.78 | 9.11±0.33 | 3.59 ± 0.33 |
| RC30 | R1 | 2.19±0.02 | 19.27±0.03 | 12.78±0.06 | 2.78±0.05 | 38.05±0.22 | 7.74±0.92 | 1.86 ± 0.52 |
| | R2 | 2.21±0.02 | 19.39±0.01 | 13.34±0.10 | 2.79±0.04 | 37.03±3.37 | 7.91±0.50 | 1.93 ± 0.50 |
| RC33 | R1 | 2.06±0.02 | 21.12±0.02 | 12.06±0.85 | 2.75±0.00 | 50.34±7.57 | 8.11±0.36 | 2.93 ± 0.36 |
| | R2 | 2.08±0.01 | 22.24±0.01 | 12.06±0.85 | 2.84±0.06 | 50.54±6.26 | 8.12±0.86 | 3.16 ± 0.86 |
| RC35 | R1 | 2.06±0.01 | 21.97±0.02 | 12.83±0.01 | 2.81±0.00 | 50.75±6.23 | 7.86±1.41 | 3.09 ± 0.47 |
| | R2 | 2.05±0.01 | 21.29±0.01 | 12.41±0.22 | 2.72±0.01 | 51.64±6.45 | 8.03±0.88 | 2.97 ± 0.31 |

Table 3. Analysis of Variance and normality test

| ANOVA | *p-value* ≤ *0.05* | | | | | | |
|---|---|---|---|---|---|---|---|
| Response variables | $\rho_b$ | $p_{ap}$ | $E_d$ | $v$ | $\sigma_c$ | $\sigma_f$ | $E_f$ |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Main factors | Particle type | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| | w/c | 0.000 | 0.000 | 0.000 | 0.001 | 0.000 | 0.000 | 0.000 |
| Interaction | Particle type* w/c | 0.000 | 0.000 | 0.000 | 0.009 | 0.000 | 0.026 | 0.005 |
| $R^2$(adj) % | | 99.84 | 99.01 | 99.58 | 96.60 | 98.63 | 99.59 | 93.45 |
| *Anderson-Darling (p-value ≥ 0.05)* | | 0.360 | 0.287 | 0.888 | 0.119 | 0.849 | 0.476 | 0.627 |

3.3.1 Bulk density

The bulk density of the cementitious composites ranges from 2.026 to 2.750 g/cm³. An interaction effect is significant with a p-value of less than 0.05 (see Table 3). Figure 4 shows the interaction effect plot for the mean bulk density. The means within the particle type factor are compared by the Tukey test, i.e., groups of similar letters indicate equality.

The silicon carbide reinforced composites reach greater densities and are attributed to the higher SiC density in relation to silica and CMF. Mineral particles, such as silica and silicon carbide, lead to increased density values, especially when w/c is at 0.33 and 0.35 (Group A, Figure 4). In contrast to cement technology, in which the lower w/c leads to higher cement paste density [25], ceramic-reinforced composites behave in the opposite way, being attributed to the interaction between the pressing process and the particle capacity to absorb water from the system, directly affecting the microstructure of the matrix phase. This characteristic may hinder the rheology of the system, especially at the lower w/c levels (0.28 and 0.30), affecting the hydration of the cement leading to a more porous structure. This effect does not occur when CMFs are incorporated, whereas the smaller amount of water (0.28 and 0.30) provides higher density material, which agrees with the cement technology, that is, lower w/c leads to the high-density cement paste [25]. It is noteworthy that these composites are obtained by cold pressing, which differs from most studies available in the literature.

[Figure 4]

3.3.2 Apparent porosity

The apparent porosity data range from 12.06% to 28.26% (Table 2). Figure 5 shows the interaction effect plot for the mean apparent porosity. Except for CMF composites, the increase in w/c reduces porosity levels. As discussed above for bulk density results, the hydrophilicity of silica and silicon carbide affects the w/c and consequently the rheology and microstructure of the cement paste. These findings imply that the effect of

lower w/c levels (0.28 and 0.30), along with the hydrophilic characteristics of silica and silicon carbide particles, hinder the total hydration of cement grains, especially for compacted composites, leading to a more porous structure. In contrast, this effect is not evident for resin-coated CMF composites, since this phase does not absorb water from the system. In this case, lower w/c levels lead to reduced porosity and increased density levels, as mentioned in section 3.2.1.

[Figure 5]

3.3.3 Flexural strength

The flexural strength data of the cementitious composites range from 7.74 to 16.38 MPa (Table 2). The interaction of the factors is significant in the flexural strength, revealed by ANOVA (p-value $\leq 0.05$) shown in Table 3. Figure 6 shows the interaction effect plot for the mean flexural strength. Higher flexural strength is achieved for composites made with silicon carbide particles. In general, a less porous cementitious material leads to a higher mechanical strength, especially under compressive loads. The bending load combines tension and compression at the lower and upper sides of the beam, respectively. The interface bonding condition plays an important role in the strength of the material, mainly when tensile loads are considered. The smooth surface of CMFs coated with resin (Figure 4C) provides a poor interface condition with the cementitious matrix phase. This feature may be responsible for the drastic decrease in flexural strength at nearly 75% by the incorporation of CMFs. It is emphasised that the length of CMFs is not sufficient to provide improvements under tensile loads, as reported in the open literature for high performance concrete reinforced with long fibres, generally from 6.3 to 76.2 mm [35].

The flexural strength is reduced when the 0.30, 0.33 and 0.35 w/c levels are considered, as shown by the same group letter B in Figure 7. Higher strength is obtained for composites made with 0.28 w/c, which agrees with the less porous CMF composite, but not for silica and silicon carbide composites, which revealed higher levels of porosity (Figure 6). This behaviour can be attributed to the fracture mode under bending loads, especially related to the tensile side of the beam. Further investigations should be conducted to better assess the mode of fracture such composites under bending.

[Figure 6]

3.3.4 Flexural modulus

The flexural modulus data of the cementitious composites range from 1.86 to 5.69 GPa (Table 2). As shown in Table 3 (p-value $\leq 0.05$), the interaction of the factors

significantly affects flexural modulus (Figure 7). The flexural modulus is increased to higher w/c when silica and silicon carbide are used. Silica and silicon carbide lead to similar flexural modulus behaviour. The stiffness of brittle composite material is quite affected by its matrix phase. As previous mentioned, the low level of w/c may not be sufficient to hydrate the cement paste, reducing the stiffness of the composites. In contrast, this effect is not so evident for CMF composites, where the coated fibres do not absorb water from the system, thereby leading to similar hydration conditions of the matrix phase.

[Figure 7]

3.3.5 Compressive strength

The compressive strength data for the cementitious composites range from 27.18 to 72.36 MPa (Table 2). The p-value less than 0.05 (see Table 3) reveals a significant interaction effect, as shown in Figure 8. Lower levels of porosity were obtained by silica-reinforced composites (Figure 8), in which present higher compressive strength values (Figure 8). It should be noted that the CMF achieves higher strength than silicon carbide reinforced composites. They presented similar porosity levels at 0.33 and 0.35 w/c (Figure 6). The higher aspect ratio of CMFs contributes to retard crack propagation and increase the ultimate compressive stress of the composites [35]. It is noted the w/c does not affect the compressive behaviour of the composites made with CMF and silicon carbide. The levels of 0.33 and 0.35 w/c provide similar (Group A) and higher strength when combined with silica particles.

[Figure 8]

3.3.6 Dynamic modulus of elasticity

The dynamic modulus data vary from 12.06 to 33.72 GPa corresponding to RC33 and Sil33 conditions, respectively. This response is affected by the interaction of the factors, as shown in Table 3 (p-value $\leq 0.05$). Figure 9 exhibits the interaction effect plot for the dynamic modulus, revealing a reduction in dynamic modulus by increases of the w/c, especially for silicon carbide reinforcement. The highest dynamic modulus is achieved by silicon carbide particles, followed by silica and CMF. Despite the high stiffness of the carbon fibre, the coating of epoxy polymer decreases its elastic modulus and consequently affects the dynamic modulus of the composites.

[Figure 9]

3.3.7 Microstructural analysis

Figure 10 shows backscattered electron images (BEI) for silicone reinforced composites at different w/c levels. Chemical components of high electron density have high backscatter coefficients and appear bright in the backscattered images. As the non-hydrated components in cement have much higher electron backscatter coefficients than the hydrated products, these residual non-hydrated cement grains appear brighter in BEI. The difference in grey level represent differences in internal porosity, while the darker zones corresponds to the pore formation [36]. Figure 10 (A, B) is brighter than Figure 10 (C, D) being attributed to the presence of unhydrated cement products due to the absence of water at lower w/c levels. Figure 6 also shows the increase in porosity when the reduced amount of water is available within silicon carbide composites. A higher amount of pores, represented by black spots, is also shown when low w/c levels are used (Figure 10 A, B).

[Figure 10]

Figure 11 shows BEI of silica reinforced composites at different w/c levels. The presence of macro pores is more susceptible in those sample made with low w/c level (Figure 11A,B), as shown similarly by silicon carbide composites (Figure 10). As previously discussed, the hydrophilic characteristics of the mineral particles amplify the lack of water, especially for compacted samples at low w/c.

[Figure 11]

Figure 12 shows BEI of CMF composites at different w/c ratios. Despite the porosity results shown in Figure 6 have pointed out higher porosity levels at 0.33 and 0.35 %wt., no significant variation of the microstructure is revealed in Figure 12. A fibre pull-out mechanism is evidenced in these images, which indicates a poor interfacial adhesion between fibre-matrix phases. This fracture mode is in accordance to the massive reduction achieved by CMF composites under bending loads (Figure 7).

[Figure 12]

3.3.8 Porous aerostatic bearings test

A porous restrictor requires a balance between the mechanical behaviour and the porosity levels of the material. Based on the previous composite characterisation, three different composites were chosen to be evaluated as porous restrictor of aerostatic bearings. The silica and silicon carbide composites were chosen at 0.30 w/c, taking into account the requirement of a porosity range of 20 to 35% [5, 8, 32]. Since CMF composites have reached a small variation in porosity, a 0.28 w/c was chosen based on their enhanced mechanical properties at this level (Figures 6, 7 and 8). Table 4 shows the

oxygen permeability coefficient measured for the selected composites, which are within the working range ($6.5 \times 10^{-16}$ and $8.4 \times 10^{-14}$ $m^2$ [5, 8, 32]) for porous bearings. It is worth noting that CMF composites at 0.28 w/c achieved a lower porosity level than SiC composites at 0.30 w/c (Figure 6), however CMF composites reach a higher permeability coefficient being attributed to the high aspect ratio of CMF and its poor adhesion with the cement matrix (Figure 12), which facilitates the flow of air through the material.

Table 4. Results for oxygen permeability properties of cementitious composites

| *water / cement factor* | *φ - oxygen permeability (x 10 $^{-16}$ m²)* | | |
|---|---|---|---|
| | *Silica* | *Silicon carbide* | CMF |
| 0.30 | 8.17±0.72 | 15.99±2.83 | - |
| 0.28 | - | - | 51.92±5.89 |

Figure 13 shows the loading carrying capacity of the three porous cementitious bearings at 1 bar (14.4 psi) and 2 bar (28.8psi) working pressure. The maximum load applied was 27.05 N, due to the limitation of the device. The silica composite porous bearing underwent pneumatic instability (hammer effect) operating at loads above 15 N. This behaviour can be attributed to its lower permeability coefficient ($8.17 \times 10^{-16}$ m²) as shown in Table 4. The silicon carbide porous bearing obtained a promising behaviour in a stable operation with loads greater than 15 N, maintaining thickness air gap of 60 μm at 1 bar and 80 μm at 2 bar. The CMF reinforced bearings achieved the lowest air gap variation of 25.0 to 41.1 μm at 1 bar and 46.1 to 53.3 μm at 2 bar. Aerostatic bearings are rarely designed to operate at gaps greater than 20 μm, where gas consumption would increase significantly, making bearing operation considerably less economical. In addition, the lower air bearing gaps provide a more stable working condition [5, 8, 32]. In this case, for this tested load range, CMF-made cementitious bearings are promising for engineering applications. In terms of mechanical strength, all the composites satisfy the application in the pressure range evaluated in this work. Higher load capacities and pressure levels will be the scope of future investigations.

[Figure 13]

A porous restrictor with high stiffness and strength is required to withstand higher working pressures and load capacity [5, 8, 26]. However, the permeability and the

connectivity of the pores are extremely important to achieve stable operations. In this work, although higher stiffness and strength were achieved mainly by silicon carbide and silica particle inclusions, the carbon micro fibre (CMF) composites obtained the most appropriate permeability levels for such application. The design of high stiffness and strength composites with adequate permeability coefficient can still be considered a challenge, as well as motivation for further investigations in this field.

## 4. CONCLUSIONS

A full factorial design was conducted to evaluate the effect of particle type and w/c factor on the physical and mechanical properties of cementitious composites to be used as porous restrictor in aerostatic bearings. The main conclusions are:

i. All responses, bulk density, apparent porosity, dynamic modulus, flexural and compressive strength were affected by the interaction of the factors, particle type and w/c.

ii. The bulk density data ranged from 2.026 to 2.750 g/cm³. Higher bulk density was obtained by adding silicon carbide particles especially at higher w/c (0.33 and 0.35).

iii. The apparent porosity data ranged from 12.06% to 28.26%. Except for CMF composites, the increase in w/c reduces porosity levels. Silica reinforced composites at 0.35 w/c achieved the lowest porosity level.

iv. The flexural strength data ranged from 7.74 to 16.38 MPa. Higher flexural strength is achieved for composites made with silicon carbide particles at 0.28 w/c level. The smooth surface of CMFs led to a poor interface adhesion with a significant reduction in strength.

v. The flexural moduli varied from 1.86 to 5.69 GPa. Composite made of silica or silicon carbide achieved higher flexural moduli. The results implied the hydration of cement matrix (w/c) plays a role in the composite stiffness.

vi. The compressive strength data ranged from 27.18 to 72.36 MPa. Higher compressive strength was achieved by the silica incorporation at 0.33 w/c.

vii. The dynamic modulus data ranged from 12.06 to 33.72 GPa. The highest dynamic modulus is achieved by silicon carbide particles, followed by silica and CMF at 0.28 w/c.

viii. The microstructural analysis revealed increased porosity of silica and silicon carbide composites by the reduction in w/c, being attributed to the hydrophilic

characteristics of the particle to absorb water from the system. A fibre pull-out mechanism is evidenced for CMF composites indicating a poor interfacial adhesion between fibre-matrix phases.

ix. The cementitious composites achieved acceptable permeability coefficient for porous bearing applications with higher values for CMF composites.

x. The cementitious composites were tested at 1 and 2 bar under a load capacity up to 27.05 N without structural failure. The CMF reinforced bearings achieved the lowest air gap variation of 25.0 to 41.1 μm at 1 bar and 46.1 to 53.3 μm at 2 bar, being promising for precision engineering applications.

Higher load capacities and pressure levels will be the scope of future investigations.

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**Figure Captions:**

Figure 1. Porous aerostatic bearing system (A) and porous restrictors (B).

Figure 2. XRD patterns of cementitious composites reinforced with silica (A) and silicon carbide (B).

Figure 3. SEM images of the silica particles (A), silicon carbide (B) and CMF (C).

Figure 4. Interaction effect plot for the mean bulk density.

Figure 5. Interaction effect plot for mean apparent porosity.

Figure 6. Interaction effect plot for the mean flexural strength.

Figure 7. Interaction effect plot for the mean flexural modulus.

Figure 8. Interaction effect plot for the mean compressive strength.

Figure 9. Interaction effect plot for the mean dynamic modulus.

Figure 10. BEI of silicon carbide composites at w/c: (A) 0.28, (B) 0.30, (C) 0.33 and (D) 0.35.

Figure 11. BEI of silica composites at w/c: (A) 0.28, (B) 0.30, (C) 0.33 and (D) 0.35.

Figure 12. BEI of CMF composites at w/c: (A) 0.28, (B) 0.30, (C) 0.33 and (D) 0.35.

Figure 13. Curves of static load capacity for the bearings with porous cementitious restrictor.