

1 **Lightweight Alkali-Activated Material from Mining and**
2 **Glass Waste by Chemical and Physical Foaming**

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15 **ABSTRACT**

16 A foamed alkali-activated material (FAAM), based on tungsten mining waste (TMW)
17 and municipal waste glass (WG) was fabricated by using aluminium powder and
18 organic surfactant foaming agents. The compressive strength and density of the FAAM
19 were investigated in terms of different parameters of production and formulation
20 including curing temperature as well as the dosage of Na₂O, foaming agent, foam
21 catalyzing agent and stabilizing agent. FAAM made with aluminium powder consisted
22 of smaller open macropores and exhibited higher compressive strength in comparison
23 with those of larger closed macropores obtained by the organic surfactant
24 counterparts. The final aluminium powder based FAAM reached a 7-day compressive
25 strength in excess of 3 MPa and a density below 0.7 g/cm³. The implementation of an
26 appropriate amount of foam stabilizer led to a further 15% increase in compressive
27 strength, 6% reduction in density and a thermal conductivity below 0.1 W/mK. The
28 FAAM explored in this study represents an ideal material for building envelop
29 insulation.

30 **Keywords:** Alkali-activation; aluminium powder; compressive strength; foamed
31 cementitious materials; geopolymer; waste glass; waste materials

32

33 **1. Introduction**

34 The development and application of lightweight cementitious materials have in the
35 past decades grown very rapidly and such materials are among the leading technology
36 in the “special purpose” concrete category [1]. Autoclaved aerated concrete (AAC) is
37 primarily used for making lightweight blocks to build partition walls. The lightweight
38 nature of the blocks means that they impose a minimum loading on the building and
39 provide good thermal and sound insulation [2]. Pre-fabricated panels can also be
40 made from lightweight cementitious materials with the latest innovation being hollow-
41 core, interlocking panels [3]. Another useful application of lightweight cementitious
42 materials is void filling for structural stabilisation of disused structures [4].

43 Approximately 70% of heat energy is lost through the building envelope from typical
44 residential housing without proper thermal insulation [5], making building insulation
45 one of the fastest growing applications of lightweight cementitious materials [4].

46 The industry has been working hard to develop eco-friendly and energy efficient
47 construction materials due to the increase in market demand. With the exception of
48 organic insulation materials, which are based on a renewable and recyclable material,
49 polymer-based insulation materials are associated with a host of environmental
50 hazards in terms of toxicity. Polymer foam materials such as polystyrene and
51 polyethylene remain very popular materials for insulation and make up almost half of
52 the market [6]. Polystyrene is classified as a possible human carcinogen [7], and the
53 production of Expanded Polystyrene Foam (EPS) has a global warming potential
54 (GWP) 7 times greater than carbon dioxide [8]. Hence, the use of lightweight
55 cementitious materials can constitute an effective way of energy-conservation and
56 environmental-protection, particularly for the thermal-insulation engineering of
57 buildings.

58 Currently, technologies for insulating performance are being explored, like aerogels
59 [9] and Vacuum Insulating Panels (VIPs) [10]. However, these cannot be produced in
60 a cost-effective manner and are too fragile to meet the durability needs that are critical
61 for mainstream building products (e.g. VIPs cannot be nailed, and lose thermal
62 resistance rapidly if perforated), making them impractical solutions for today's building
63 environment.

64 There were several recent studies about lightweight foamed alkali-activated materials
65 (AAM), which are referred to as geopolymers in some literature as well, based on fly
66 ash [11] and bottom ash [12]. AAMs have been demonstrated to possess many of the
67 necessary qualities a lightweight cementitious material should display, namely high
68 temperature resistance [13], low shrinkage [14], low coefficient of permeability [15],
69 low thermal conductivity [16] and good nailability [17]. Also, the appeal of being able
70 to use high volumes of industrial waste materials for the production of AAMs and thus
71 contest the environmental pollution of Portland cement is an added benefit.

72 So far, in building applications, the research into foamed alkali-activated materials
73 (FAAMs) is limited to structural grade concrete with mid-range densities of 1300-1700
74 kg/m³ and compressive strengths of 13-15 MPa [13], [18]–[20]. Out of the few studies
75 conducted to produce high-performance FAAMs, the resulting materials possessed
76 either high insulating properties coupled with very low compressive strength [21] or
77 high compressive strength coupled with poor thermal insulating properties [16].
78 However, to the author's best knowledge, the use of FAAMs as a high-performance
79 insulation material with high mechanical resistance and low thermal conductivity has
80 not been proven.

81 In this study, the potential of producing a high-performance FAAM made entirely from
82 tungsten mining waste and municipal waste glass which could satisfy not only thermal
83 performance but also mechanical strength requirements of similar grade products was

84 investigated. The compatibility of a natural foam catalyser and foam stabilising agent
85 were investigated in order to improve both the thermal insulation and compressive
86 strength performance. In addition, the preparation of a FAAM using mechanically pre-
87 formed foam composed of an anionic surfactant and the alkali-activator, never
88 reported in previous works, was studied.

89 **2. Materials and Methods**

90 **2.1 Materials and chemicals**

91 The precursor materials used to produce the FAAM in this investigation consisted of
92 tungsten mining waste (TMW) and municipal waste glass (WG). The TMW was
93 derived in powder form from the Panasqueira mine in Castelo Branco, Portugal, while
94 the WG was received from the local municipality of Covilhã, Portugal. The micro-
95 morphology of the TMW and WG can be seen in our previous study [22]. The chemical
96 composition of TWM and WG from a sequential benchtop wavelength dispersive X-
97 ray fluorescence (WD-XRF) spectrometer (Supermini200, Rigaku, Japan mounted
98 with LiF(200) and PET crystals), is shown in Table 1. The raw materials used for the
99 alkali activator were 98% pure sodium hydroxide (NaOH) (SH) (Fisher Scientific,
100 Germany), and sodium silicate (Na₂SiO₃) (SS) (Solvay SA, Portugal).

101

102 **Table 1.** Chemical composition (wt %) of TMW and WG determined by WD-XRF

Component	TMW	WG
Na ₂ O	0.51	12.44
MgO	2.16	1.76
Al ₂ O ₃	14.89	2.12
SiO ₂	49.17	68.71
SO ₃	8.98	0.33
K ₂ O	2.92	0.77
Fe ₂ O ₃	13.69	1.48
CaO	0.58	10.04
P ₂ O ₅	0.32	0.00
TiO ₂	0.5	0.00
ZnO	1.25	0.00
CuO	0.32	0.00
As ₂ O ₃	4.26	0.00

103 Foaming was achieved by either a chemical foaming technique or physical foaming
 104 technique. Aluminium powder (purity of 99 %, average particle size of 75 microns and
 105 molar mass of 26.98 g/mol, Sigma Aldrich, UK) was used as the foaming agent of the
 106 chemical foaming technique. Sodium dodecyl benzenesulfonate (SDBS, Sigma
 107 Aldrich, UK, molecular weight of 348.48 g/mol), was used for the physical foaming
 108 technique due to its ionic nature and thus enhanced foam stability compared to non-
 109 ionic surfactants [23].

110 Manganese dioxide (MnO₂, particle size of less than 10 microns and a molecular
 111 weight of 86.94 g/mol, Sigma Aldrich, UK) was used to catalyse the reaction of the
 112 chemical foaming process. Also, starch (Sigma-Aldrich, UK) which is a natural, high-
 113 polymeric carbohydrate was used to stabilise the chemical foaming process.

114 **2.2 Methods**

115 Firstly, essential parameters associated with the production of a FAAM were
116 investigated, namely the curing temperature and dosage of Na₂O (mass ratio of total
117 Na₂O in the activating solution to precursor). The optimum curing temperature and
118 dosage of Na₂O in terms of density were used as benchmarks and carried forward to
119 produce the reference sample for evaluating the effects of manganese dioxide and
120 starch.

121 The mix parameters analysed through a laboratory experiment of 18 TMW-WG-FAAM
122 samples were curing temperature (40°C, 60°C, 80°C and 100°C), dosage of Na₂O
123 (3.1%, 3.3% and 3.5%), wt.% of aluminium powder (3, 6 and 9), wt.% surfactant (2, 4
124 and 6), wt.% MnO₂ (0.2, 0.4 and 0.6) and wt.% starch (2, 4 and 6).

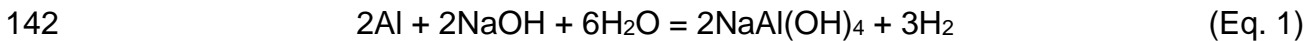
125 All sample preparation was carried out in a laboratory maintained at 20°C. For the
126 preparation of the non-foamed base TMW-WG-AAM, the synthesis conditions for
127 achieving the highest strength and satisfactory workability were adopted based on
128 previously published results [24]. The precursor consisted of TMW and WG with a
129 mass ratio of 3:2. The alkali activating solution consisted of 10M sodium hydroxide
130 solution (plus the sodium silicate concentration) and 8 wt.% of water. The mass ratio
131 of the alkali activating solution and precursor was fixed at 0.22.

132 To determine the relationship between the various parameters and indicators, the
133 horizontal x-axis presented the parameters, i.e. curing temperature, dosage of Na₂O
134 (in %), foaming agent, manganese dioxide and starch contents, while the vertical y-
135 axis' presented the average of the assessment indicators, i.e. compressive strength
136 and density.

137

138 **2.2.1 Chemical Foaming Method**

139 The principle of chemical foaming with aluminium powder is based on the reaction
140 between aluminium and SH to produce H₂ gas, which initiates the expansion of the
141 system according to the following chemical reaction formula [25]:

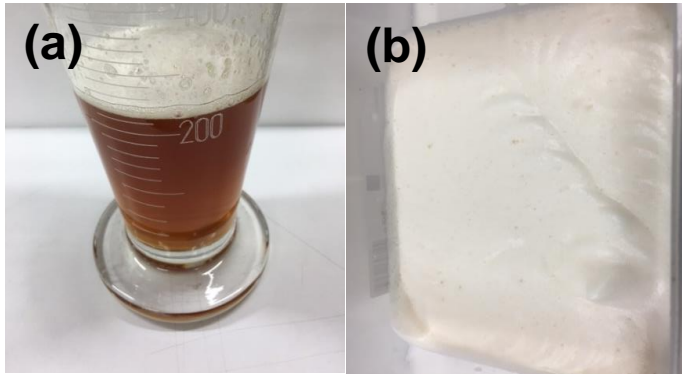


143 The TMW and WG were dry-blended in a commercial mixer at 300 rpm for five
144 minutes, forming the precursor materials. The alkali activating solution was slowly
145 added to the precursor materials and then stirred for 2.5 minutes at 200 rpm, followed
146 by 2.5 minutes at 500 rpm to form the AAM paste. The aluminium powder was
147 subsequently added to the AAM by weight of sodium hydroxide and stirred for a further
148 1 minute at 350 rpm. Plastic 4 x 4 x 16 cm³ molds were filled with the paste in two
149 stages. The TMW-WG-FAAM was then left to rest until the foaming process was
150 complete. The rest period depended on the quantity of aluminium powder and the
151 dosage of Na₂O since different combinations produced different rates of expansion.

152 **2.2.2 Mechanically Pre-Formed Foaming Method**

153 The anionic surfactant and the alkali activating solution were combined together (Fig.
154 1a) and then mixed at 1200 rpm for 5 minutes to form the foamed alkali activating
155 solution (Fig. 1b). TMW and WG were dry-blended in a commercial mixer at 300 rpm
156 for 5 minutes, forming the precursor materials and the foamed alkali activating solution
157 was mixed into the precursor at 300 rpm for 5 minutes (Fig 1c). Finally, Fig. 1d exhibits
158 the fresh surfactant TMW-WG-FAAM immediately after mixing. A beater attachment
159 was used for the mixing to allow more air to be entrapped into the TMW-WG-FAAM.

160



161



162

163 **Fig. 1.** Preparation of surfactant TMW-WG-FAAM showing (a) the alkali activator/surfactant mixture (b)
164 prepared foam (c) combination of the precursors and foam (d) surfactant TMW-WG FAAM

165

166 **2.2.3 FAAM Heat Curing Method**

167 The specimens were placed in a temperature and humidity controlled environmental
168 chamber at 95 %RH. The curing temperature was initially evaluated between 40°C
169 and 100°C, with the most appropriate temperature in terms of compressive strength
170 carried forward for the production of subsequent FAAM samples. After 24 hours of
171 curing, the prismatic FAAM samples were demoulded and each of them was then cut
172 into three 40 x 40 x 40 mm³ cubes.

173 **2.2.4 Thermal Conductivity**

174 The thermal conductivity was measured with a thermal conductivity meter (Fox 200,
175 TA Instruments, USA). The steady state heat flux through the 150 x 150 x 25 mm³
176 rectangular block samples were measured for a temperature gradient of 10°C between
177 the upper and the lower face of the sample. Three identical samples for each TMW-

178 WG-FAAM were measured for evaluation of the thermal conductivity. Before
179 measurement, the samples were left for 12 h at 80°C and placed in a dry chamber for
180 cooling for 30 minutes without moisture absorption.

181 **2.2.5 Compressive Strength**

182 The compressive strength of the TMW-WG-FAAM cubes was tested after 7 days in
183 accordance with EN 196-1 using a 50kN universal testing machine (Instron 5960, UK)
184 at a constant loading rate of 3 kN/min. The compressive strength value was the
185 average of values obtained from three specimens.

186 **2.2.6 Imaging**

187 TMW-WG-FAAM samples were vacuum impregnated with epoxy resin doped with a
188 fluorescent dye (EpoDye, Solvent Yellow 43, Denmark) to highlight the pores. The
189 samples were polished using a bench-top planar grinding machine (PlanarMet 300,
190 Buehler USA) and imaged using a fluorescence microscope (Leica M205 FCA, UK).
191 Images were analysed using open source software (ImageJ) using a sample surface
192 area of 22 x 22 mm.

193 **3. Results and Discussion**

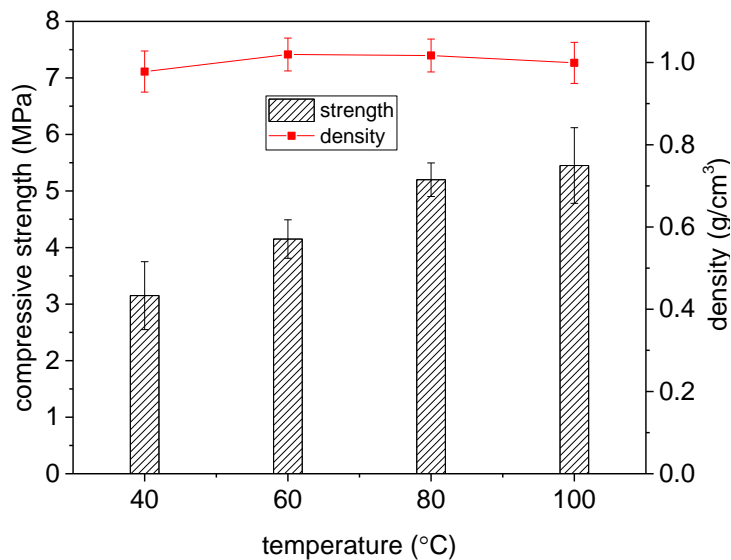
194 **3.1 TMW-WG FAAM by chemical foaming technique**

195 **3.1.1 Effect of heat curing**

196 Fig. 2 shows the effect of curing temperature on the 7-day compressive strength and
197 density of the TMW-WG-FAAM samples using 6% wt. of aluminium powder, a Na₂O
198 of 3.1% and additional 8% wt. of mixing water. It is evident the compressive strength
199 of the sample increased with curing temperature, while the density remained in
200 practical terms unchanged within the range of 0.97 and 1.01 g/cm³. As expected, the
201 lowest compressive strength was attained by the sample cured at the lowest
202 temperature (i.e. 40°C), reaching 3.15 MPa. Likewise, the compressive strength
203 increased with increase in curing temperature due to the accelerated ion diffusion rate

204 between the liquid and solid material thus producing a denser colloidal structure [26].
205 TMW-WG-FAAM samples cured at the highest temperature, i.e. 100°C obtained a
206 compressive strength of 5.45 MPa. The ultimate compressive strength and density of
207 the samples were not found to be interdependent, and thus the optimal curing
208 temperature of TMW-WG-FAAM may be based on a compromise of the compressive
209 strength. In this case, the 80°C cured sample attained only a 4.6% lower compressive
210 strength over the 100°C cured sample but consumed approximately 40 kWh less
211 energy during curing (based on the energy performance of a Weiss C340-40 model
212 environmental chamber operating for 24 hours). By considering the energy
213 consumption during manufacturing, mechanical performance and thermal resistance,
214 curing at 80°C was chosen to be the optimum curing temperature, in line with results
215 obtained by other studies [27] and thus used for the preparation of all subsequent
216 samples.

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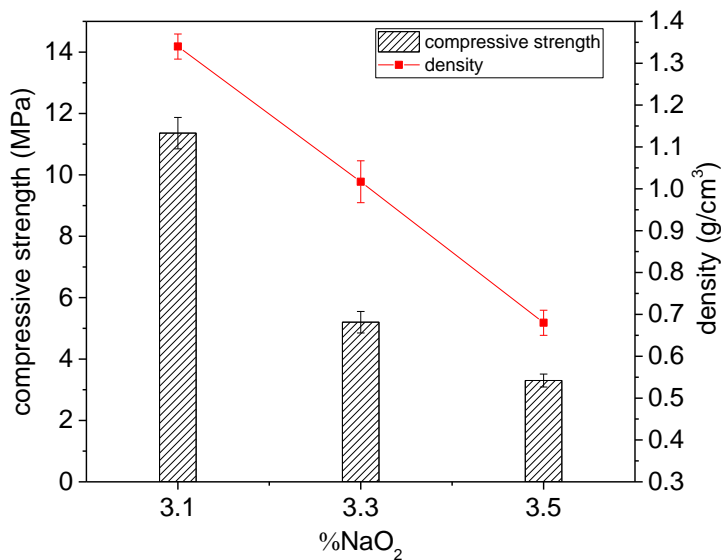


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219 **Fig. 2.** Effect of curing temperature on compressive strength and density of aluminium powder TMW-
 220 WG FAAM

221 3.1.2 Effect of dosage of Na₂O

222 Fig. 3 demonstrates the effect of the 3.1%, 3.3% and 3.5% of Na₂O on the 7-day
 223 compressive strength and density of the TMW-WG-FAAM samples made using 6%
 224 wt. of aluminium powder and 8% wt. of mixing water. It was clear that the density of
 225 TMW-WG-FAAM reduced with increase of the %Na₂O. The formation of H₂ gas led to
 226 a foaming effect which would be enhanced with the increase of SH. Increasing the
 227 dosage of Na₂O from 3.1% to 3.5% reduced the density by 49% from 1.34 g/cm³ to
 228 0.67 g/cm³. The increased foaming increased the porosity and reduced the density,
 229 but was naturally coupled by a reduction in the compressive strength of the TMW-WG-
 230 FAAM. In this case, the compressive strength reduced from 11.36 MPa to 3.3 MPa.
 231 Under normal circumstances, aluminium does not react with water, as an impermeable
 232 protective layer composed of aluminium hydroxide forms within seconds [25]. With the
 233 addition of sodium hydroxide, the aluminium hydroxide goes into solution, and
 234 the layer of aluminium oxide previously formed by passive corrosion is dissolved. For
 235 this reason, the alkali activating solution with a low Na₂O (less than 3.1%) involved a
 236 very slow reaction due to insufficient SH, leading to reduced volumetric expansion of
 237 the foam.



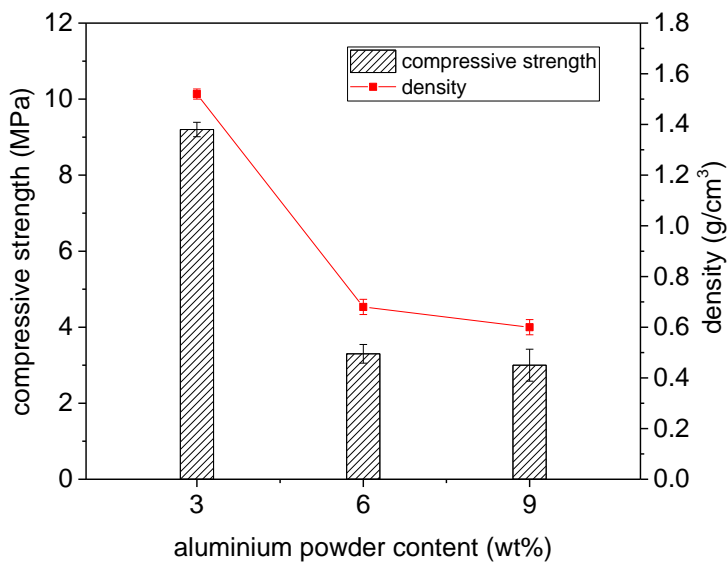
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239 **Fig. 3.** Effect of %NaO₂ on compressive strength and density of aluminium powder AAFM

240 **3.1.3 Effect of aluminium powder content**

241 Fig. 4 shows the effect of 3% wt., 6% wt. and 9% wt. aluminium powder dosage on the
 242 7-day compressive strength and density of the TMW-WG-FAAM sample made using
 243 dosage of Na₂O of 3.5% and 8% wt. mixing water. The sample density obtained with
 244 3% wt. of aluminium powder was 1.52 g/cm³, which went on to decrease to 0.68 g/cm³
 245 and 0.6 g/cm³ for 6% wt. and 9% wt. aluminium powder dosages, respectively. The
 246 compressive strength also experienced a reduction by 67% from 9.2 MPa to 3 MPa,
 247 respectively. The reduction in compressive strength with increase in aluminium
 248 powder dosage was expected and due to the straightforward fact that more aluminium
 249 powder was available to react with the SH, producing more H₂ gas. Additionally, the
 250 high reaction rate between the aluminium powder and SH would have also led to the
 251 premature depletion of SH, reducing its availability for the required dissolution of
 252 aluminosilicate precursors; a factor known to interrupt the attainment of mechanical
 253 strength in AAMs [28]. It can also be deduced that the extent to which the foaming
 254 action and thus reduction in density occurs is less dominant with the increase of
 255 aluminium powder than with the increase of the alkali content i.e. %Na₂O. The latter

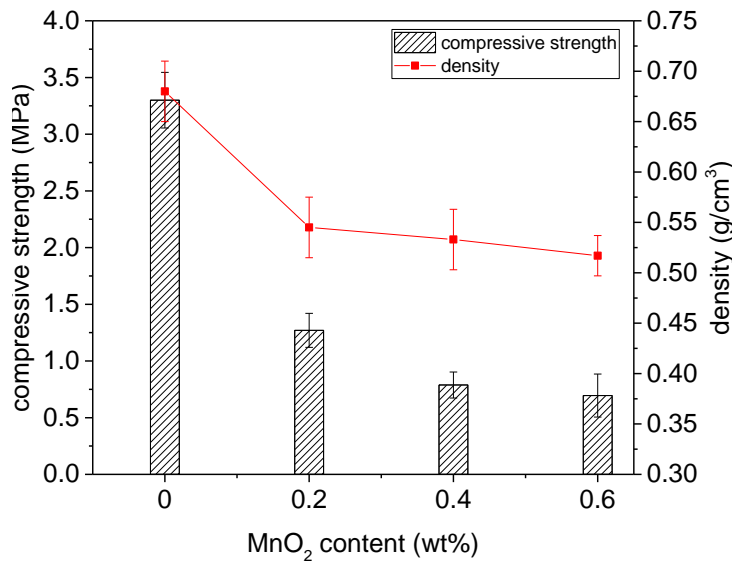
256 would make the alkali content and thus the appropriate optimisation of the activating
257 solution the controlling factor in aluminium powder FAAMs.



258
259 **Fig. 4.** Effect of aluminium powder on compressive strength and density of aluminium powder FAAM

260 3.1.4 Effect of manganese dioxide content

261 Fig. 5 compares the effect of 0.2% wt., 0.4% wt. and 0.6% wt. manganese dioxide
262 catalysing agent dosage on the 7-day strength of TMW-WG-FAAM sample made
263 using 6% wt. aluminium powder, 3.5% dosage of Na₂O and 8% wt. mixing water. With
264 the initial presence of 0.2% wt. manganese dioxide, it is observed that the compressive
265 strength of TMW-WG-FAAM significantly dropped by 61% from 3.3 MPa to 1.27 MPa.
266 From 0.2 to 0.4 wt% and finally to 0.6 wt%, there appeared to be much steadier
267 reduction in the density and compressive strength. The large initial drop and
268 subsequent gradual reduction in density and thus compressive strength was due to
269 the thermite reaction between the manganese dioxide and the aluminium powder
270 foam. With the presence of manganese dioxide the foaming action was observed to
271 be more unstable, resulting in excessive bubble size and their subsequent rupture.
272 Therefore, it could be concluded that the incorporation of manganese dioxide should
273 be avoided in aluminium powder FAAMs.



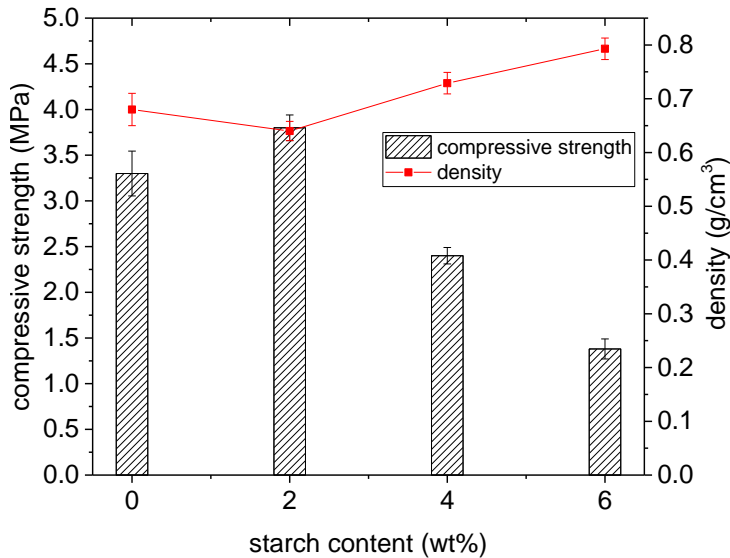
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275 **Fig. 5.** Effect of manganese dioxide on compressive strength and density of 6% wt. aluminium powder
 276 TMW-WG FAAM

277 3.1.5 Effect of starch content

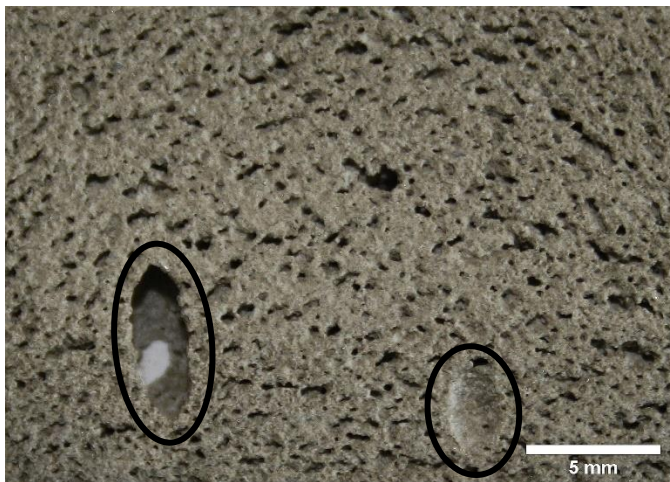
278 Fig. 6 shows the effect of 2% wt., 4% wt. and 6% wt. starch on the density and
 279 compressive strength of TMW-WG-FAAM made with 6 wt% aluminium powder, 3.5%
 280 Na₂O and 8 wt% mixing water. With the addition of 2% wt. starch, the density only
 281 marginally reduced from 0.68 g/cm³ to 0.64 g/cm³, while the compressive strength
 282 showed more noteworthy increase from 3.3 MPa to 3.8 MPa. This indicated that starch
 283 did not necessarily participate in the chemical foaming process but however improved
 284 the compressive strength. Starch being a polysaccharide was likely able to achieve
 285 this improvement in compressive strength due to its aggregating action in
 286 aluminosilicate interparticle bonds [29]. Nonetheless, when the starch concentration
 287 increased to 4% wt. and followed by 6% wt, the compressive strength significantly
 288 decreased, coupled by the increase in the density. The addition of starch above 2%
 289 wt. increased the relative concentration of particles in the system thus increasing the
 290 reaction time and subsequent formation of reaction products. The loss of compressive
 291 strength could be explained by the reduced liquid-solid ratio due to the low molecular
 292 weight of starch, resulting in a prolonged coagulation time of the FAAM and reduced

293 paste fluidity. The reduced fluidity due to the increased starch content created an
294 open-textured material, and as revealed in Fig. 7, allowed the bubbles to coalesce
295 (circled in black), and the H₂ gas generated during the aluminium powder and SH
296 reaction to escape.



297

298 **Fig. 6.** Effect of starch on compressive strength and density of aluminium powder TMW-WG FAAM



299

300 **Fig. 7.** TMW-WG FAAM made with 6% wt. starch

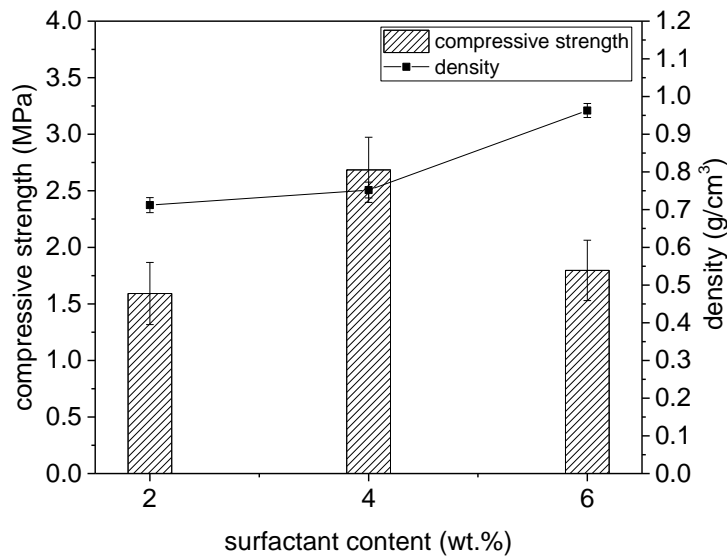
301 **3.2 TMW-WG FAAM by physical foaming technique**

302 2% wt., 4% wt and 6% wt. anionic surfactant were investigated in the preparation of
303 the surfactant TMW-WG-FAAM. In all cases, the precursor-to-foam ratio was
304 maintained at a constant ratio of 0.6.

305 **3.2.1 Effect of surfactant content**

306 Fig. 8 compares the effect of 2% wt., 4% wt and 6% wt. anionic surfactant on the
307 compressive strength and density of the TMW-WG-FAAM samples made with 3.5%
308 of Na₂O and 8 wt% mixing water. The compressive strength of the samples was
309 observed to increase with an increase in the dosage of surfactant from 2% wt. to 4%
310 wt. by 40% from 1.59 MPa to 2.68 MPa, respectively. However, the density remained
311 steady between 0.71 and 0.75 g/cm³. The increase in surfactant from 2% wt. to 4%
312 wt. did not lead to an entrainment of more air in the sample thus explaining the
313 approximately constant density. Upon the addition of 6% wt. surfactant, the density of
314 the sample increased coupled by a reduction in the compressive strength. A likely
315 explanation of the foaming inhibition with increased amounts of surfactant may be due
316 to the presence of Ca⁺ and Mg⁺ ions from the precursor materials i.e. the TMW and
317 WG which would have a strong affinity to the negatively charged carboxylate end of
318 the surfactant molecule. This would essentially deactivate the surfactant and thus
319 interrupt the foaming. Furthermore, increased surfactant content may have also led to
320 an unnecessary high foam content, increasing the drainage of water around the foam
321 thus increasing the likelihood of bubble collapse. However, further tests of increased
322 surfactant content will have to be performed to confirm its impact on the compressive
323 strength of TMW-WG-FAAM.

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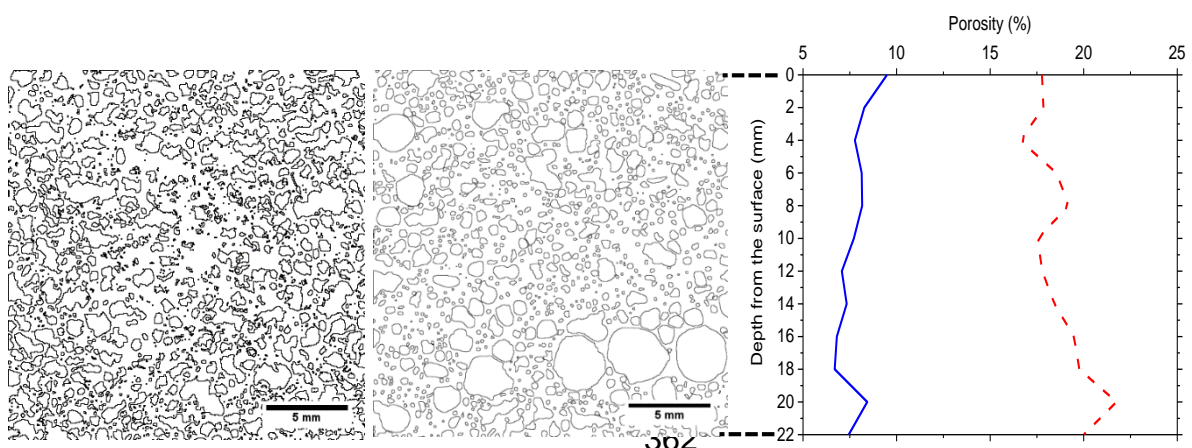
326 **Fig. 8.** Effect of surfactant on compressive strength and density of surfactant TMW-WG-FAAM

327 **3.3 FAAM Pore Imaging and Thermal Conductivity**

328 Grey level histogram analysis followed by a noise cleaning process were performed
 329 on medium magnification grey-scale surface images of TMW-WG-FAAM made with
 330 aluminium powder and surfactant. This procedure revealed clear outlines of all the
 331 pores and allowed for the calculation of their size by dividing the sum of their pixels by
 332 the total pixels in the image. Images of the deconvoluted TMW-WG-FAAM pore
 333 structures are presented in Fig. 9. TMW-WG-FAAM made by chemical foaming
 334 technique in Fig. 9a shows that most of the pore walls, or surfaces of the pores, are
 335 broken and interconnected, indicating that an open pore structure formed during
 336 foaming between the aluminium powder and SH. In comparison, most of the pores in
 337 TMW-WG-FAAM by physical foaming technique shown in Fig. 9b are spheroidal but
 338 possess little connectivity, indicating that the use of a surfactant as a foaming agent
 339 leads to a closed foam structure. Also, the average area of the pores TMW-WG-FAAM
 340 by physical foaming technique, calculated at 0.127 mm² (excluding the three large
 341 pores at the bottom right which are assumed to have formed during compaction) was
 342 10% lower than the average pore size of the TMW-WG-FAAM by chemical foaming
 343 technique, calculated at 0.141 mm². It is the former open cell structure and larger

344 average pore size of the by chemical foaming technique which would allow for more
345 air to be trapped within the material, thus leading to a lower density and thus thermal
346 conductivity.

347 Using the images in Fig. 9a and 9b, a quantification of pore area distribution using the
348 variation of the pore area fraction along the depth of the specimens were also
349 performed. The images were divided into 2 mm deep x 22 mm wide strips, and the
350 pore area fractions in each of the strips were determined. The variation of pore area
351 shown in Fig. 9c corresponds to the average of pore area fraction measurements on
352 eleven different horizontal sections for TMW-WG FAAM foamed with aluminium
353 powder and surfactant. It can be noticed that there is a lower variation with depth in
354 the pore area fraction for the TMW-WG FAAM made with surfactant. The latter
355 indicates a more uniform distribution of pores across the TMW-WG FAAM made with
356 surfactant and corroborated with observations from Fig. 9b which show it to possess
357 more spherical and uniformly distributed pores. For the TMW-WG FAAM made with
358 aluminium powder, a higher degree of variation is observed through the image
359 analysis, implying a less stable foam structure and the possibility of foam clogging,
360 particularly at the top of the sample where the porosity was determined to be
361 approximately 18% less than at the bottom of the sample.



363 **Fig. 9.** (a) Pore distribution of TMW-WG FAAM foamed with (a) aluminium powder and (b) surfactant.
364 (c) Variation of pore area fraction in TMW-WG FAAM made with aluminium powder and surfactant.

365

366 Table 2 summarises the primary TMW-WG-FAAM properties, i.e. density, 7-day
367 compressive strength and thermal conductivity for samples produced with the
368 aluminium powder and surfactant foaming agents. Due to the open pore structure of
369 TMW-WG-FAAM by chemical foaming technique, it is clear to understand why it
370 achieved a lower density of 0.64 g/cm^3 and a thermal conductivity of 0.09 W/mK . The
371 TMW-WG-FAAM by physical foaming technique achieved both a higher density and
372 higher thermal conductivity of 0.77 g/cm^3 and 0.16 W/mK , respectively due to the
373 closed pore structure and smaller average pore area. In practice, closed cell structures
374 usually possess higher compressive strengths due to the higher core density but in
375 the case of the open cell TMW-WG-FAAM by chemical foaming technique, it achieved
376 a compressive strength of 3.8 MPa compared to the closed foam structure of the TMW-
377 WG-FAAM by physical foaming technique of 2.68 MPa . This is an interesting
378 observation and leads to the postulation that the chemical foaming technique is not
379 only linked to pore characteristics such as shape and connectivity as previously
380 mentioned, but also to its strength. In this case, the TMW-WG-FAAM by chemical
381 foaming technique can be thought to have contributed to reinforcing the pore wall
382 structure; however, this would require further investigation.

383 Table 2 also lists thermo-physical properties of traditional cement-based insulation
384 materials and recently published foamed alkali-activated materials. By comparing
385 between the best performing TMW-WG-FAAM reported in this study (prepared with 6
386 wt.% aluminium powder and 2% wt. starch) and other materials, the TMW-WG-FAAM
387 significantly outperforms the traditional cement-based insulation materials such as
388 AAC, foamed concrete and cement expanded vermiculite in terms of thermal
389 conductivity while the combination of density and compressive strength is also
390 unmatched.

391 **Table 2.** Thermo-physical properties of TMW-WG-FAAM, traditional cement-based insulation materials
 392 and alkali activated foam materials

Sample	Density (g/cm ³)	Compressive strength (MPa)	Thermal conductivity (W/mK)
Unfoamed TMW-WG-AAM	2.10	61.0	0.280
6% wt. aluminium powder TMW-WG-FAAM with 2% wt. starch	0.64	3.8	0.090
4% wt. surfactant TMW-WG-FAAM	0.77	2.68	0.150
Aerated concrete (AAC) [30]	0.60	4.5	0.160
Foamed concrete [31]	0.60	5.2	0.165
'Inorganic foams' [30]	0.67	6.0	0.145
'Geopolymer foam concrete' [32]	0.60	1.3	0.470
'Geopolymer foam' [33]	0.58	4.4	0.158
'Porous fly ash-GP' [29]	0.56	1.23	0.107

393

394 **4 Conclusions**

395 This study revealed that alkali-activated foamed materials (FAAMs) based on tungsten
 396 mining waste and waste glass could be successfully prepared by a chemical foaming
 397 method using aluminium powder and a physical foaming method by using pre-formed
 398 foam with an anionic surfactant. The following conclusions can be drawn from the
 399 results of this work:

- 400 • The curing temperature of TMW-WG-FAAM influenced the mechanical strength
 401 but did not affect the density. The final pore structure is formed during the initial
 402 foaming process and thus curing temperature was chosen based on adequate
 403 compressive strength development, which in this case was 80°C.
- 404 • The alkali content is strongly related to both the density and compressive
 405 strength of TMW-WG-FAAM making it more of a dominant control factor
 406 compared to the content of aluminium powder. A NaO₂ dosage lower than 3.1%

407 involves a very slow reaction due to insufficient NaOH, leading to a reduced
408 volume of foaming.

409 • The chemical foaming method with aluminium powder resulted in the creation
410 of an open cell pore structure leading to a significantly lower thermal
411 conductivity and density, coupled with enhanced compressive strength.

412 • Use of manganese dioxide foam catalyst agent, even at relatively low levels
413 (0.2% wt.), resulted in unstable chemical foaming with aluminium powder and
414 compromised compressive strength. On the other hand, the use of starch as a
415 foam stabilising agent led to improved compressive strengths without affecting
416 the density.

417 • The combined technical and sustainable advantages of TMW-WG-FAAM make
418 it a viable route to yield insulating materials comparable to both traditional
419 cement-based insulation materials and other recently reported foamed alkali-
420 activated materials.

421

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