













335 kg/m<sup>3</sup>

excellent workability, which makes this suitable to be cast onsite [27]. A simple mixture of fly ashes + microsilica improves the interlink paste-aggregate and allows enhancements in workability and compression strength with densities between 1300 and 1900 kg/m<sup>3</sup> [28] and enhances thermal isolation [29]. Also, studies that utilized the mixture lime + microsilica shows that microsilica has great impact in physical properties of cellular concrete based on soils. The addition of microsilica improves the width and uniformity, and gives more rounded form to the pores, which results in a higher thermal isolation and better strength. Additions up to 20% of microsilica decrease density to 800 kg/m<sup>3</sup> with a compression strength of 7.5 MPa. Lastly, the mixture of fly ashes (80%) + Blast furnace slag (20%) (with hydrogen peroxide as foaming agent) has been evaluated, accomplishing the production of cellular concretes of 1270 kg/m<sup>3</sup> [30]. A new trend is the manufacturing of cellular concretes that do not come from Portland cement but instead they use geopolymers. This technology combines the advantages of cellular concrete with the chance to decrease the carbon footprint using a more sustainable material like geopolymers [31]. It has been reported the use of mixtures of type C fly ashes with an alkaline activator, generally NaOH, achieving compressive strengths up to 18 MPa at 28 days and at a curing temperature of 60 °C that cuts superficial cracks, water absorption and porosity [32]. Other authors showed the difference in form, size and distribution of the pores in a foamed concrete of this kind. The high volumetric contraction between 0.10 and 0.36% (5 to 10 times higher than conventional concrete) is what constitutes their main disadvantage [31]. Cellular concrete also was manufactured using zeolites as binder material [33]. A summary of alternative binders or cement replacement are included in Table 1.

## Foaming agents

They are responsible for controlling density and porosity of cellular concrete through the inclusion of air bubbles [3]. Hence, foaming agents rule the properties in the hardened state. The tendency of the foam to collapse during the preparation process brings some challenges in controlling the properties of cellular structures. Consequently, it is critical to improve the stability of fresh foams in order to produce high quality cellular structures using a predictable and reliable approach [34]. The effects of agent concentration used in the cellular concrete have been found mainly on the pore distribution and size, that affect the final strength [35]. The most commonly used foaming agents are synthetic and protein based, but detergents, gluconates and saponins may also be used. The way of action of a protein agent is its slow degradation that generates bubbles. As the bonds of larger molecules are broken, small hydrophobic molecules are formed. This process not only reduces surface tension, but creates interfaces for the air bubbles. The effectiveness of this kind of agents depends on temperature and pH [4]. Agents based on proteins allow a stronger pore structure and more closed, providing a stable web of empty spaces [3]. Synthetic foaming agents reduce surface tension of the dilution. They are amphiprotic substances and strongly hydrophilic, they allow more expansion, hence lower densities. However, they create a complex chemical environment and therefore the compatibility of the surfactant and the cement is critical to let the desired entry of air and the

development of the cellmicrostructure[4].The protein based agents perform according to compressive strength but synthetic agents have an easier handling, are cheaper and require less energy for long term storage [36]. The combination of the foaming agent with a particular water/cement ratio is also very important. Synthetic foaming agents lead to more stable foam concrete specimen than the ones obtained with protein ones for a fixed water/cement ratio [37].

The development of agents based on highly active synthetic enzymes with biotechnologic origins have enabled the improvement of the foam stability and expedite the pumping of the concrete. The use of new agents provide more freezing resistance and fewer requirements of mixing water without losing slump improving the finished characteristics. A mixture used as a foaming agent is made of aluminum powder and hydrogen peroxyde. Although this mixture is expansive instead of foaming, it can generate linked pores that are smaller than the ones produced by foaming agents, even in conditions of lower density [31]. Oxides and silica nanoparticles also have been used as coadjuvants in the formation of triphasic foams that enhance the strength in the bubbles boundaries. In this foams, nanoparticles are introduced in the air-water interface through a partial hydrophobing due to the adsorption of surfactants that accomplishes more stable Van- der-Walls interactions. It is possible to produce materials with densities below  $100 \text{ kg/m}^3$  with a stable and uniform pore structure and a better strength [38]. She et al. modifying the gas-liquid interface by coupling the effects of an organic surfactant and nanoparticles. They added nanosilica and hydroxypropyl methyl- cellulose to reduce coalescence of the bubbles. More homogeneous and finer pore structure is generated with the inclusion of this organic surfactant and nanoparticles[39].

Xanthan gum (with a thickening capacity) also has been utilized as the foam stabilizer to aggregate the liquid film around bubbles. This stabilizing method is shown to significantly enhance the pore size distribution[34]

## **Water**

The amount of water that is required in the manufacturing of cellular concretes depends on a lot of factors: composition of binder materials, type of filler and required workability. A low water content generates rigid mixtures and cause the bubbles to break; a high water content provokes thin mixtures that generates segregation of the materials. The W/C ratio varies from 0.4 to 1.25, the latter value is in the case of not using superplasticizer. The concrete strength is mainly ruled by the generated spaces and the evaporable water in the cement, which means that a reduction in W/C ratio is convenient to obtain high strengths. An appropriate combination of superplasticizers and mineral mixtures can reduce the water consumption for certain fluid properties [18]. Based on ACI 523.3R.93 it is recommended that the water to be used for the foamed concrete be fresh and drinking water. Organic elements may have a negative effect on the foaming agents, specifically the protein-based.

## **Aggregates and fillers**

For cellular concretes with nonstructural applications that generally are associated to a very low density, petreous aggregates are not used, but instead fillers are used that reduce the cement consumption without important increases in weight. Structural cellular concrete (densities above  $1200 \text{ kg/m}^3$ ) utilize aggregates of any origin. The most employed filler materials are industrial residues with pozzolanic activity.



Among the most widely used residues to replace natural aggregates are fly ashes. Their use has demonstrated improvement of the mechanic performance with respect to density [9,40] and a reduction on the hydration heat of 24% in the peak temperature [7]. However, the presence of this material in a mixture implies the use of higher W/C ratio which generates an increment in the water absorption of the final product [40] as well as an increment in thermal conductivity and a reduction in Poisson modulus [41]. Others fillers widely used in the production of cellular concrete are construction waste. For the specific case of recycled concrete waste, it has been determined that they do not have a significative effect on the compression strength [20]. Fired ceramic residues have been used in different proportions to replace the aggregate: 25, 50, 75 and 100%, finding an optimum replacement value of

25% generating a cellular concrete of  $1674 \text{ kg/m}^3$  with a compression strength of 25 MPa [42] and with an increase of indirect tensile strength of 50% [43]. Other materials reported in the production of cellular concrete as fillers are plastic waste of polyethylene, PVC and polystyrene. The use of this kind of waste decrease the compressive strength but improve the performance as an acoustic isolator [44] allowing lightening cellular concrete below  $500 \text{ kg/m}^3$  [45]. Among the polymer fillers, expanded polystyrene (EPS) stands out for its ability to improve the thermoacoustic insulation properties. Nonetheless, the presence of this filler affects the mechanical performance in a negative way because its presence weakens the interfacial paste-filling bond as a result of the hydrophobic nature of the EPS. According to the content of EPS the density and the fire resistance vary [6]. Also the use of lateritic soils has been reported with an optimus replacing value of 5% [46]. Alternatives as mixtures of soils + pozzolanas [47], silic powder

+ red sand + kaolin are the most recently used [48]. The best effects found are the improvement on the uniformity of pore distribution and thermal isolation. The phosphogypsum has been also reported as a filler with some binder capacity [26]. For more information see Table 1.

### **Fibers and reinforcements**

They can be used to improve foamed concrete strength; they may come from natural or synthetic origins. Some utilized fibers are alkali resistant fiber-glass, kenaf, steel, palm fiber and polypropylene fiber. The use of fiber can change the typical behavior of a cellular concrete as it introduces a ductile elastic-plastic region. The volumetric fraction of the fiber reinforcement varies between 0.25 and 0.4 of the mixture [3]. A negative effect of the fiber reinforcement is the porosity decline. The reinforcement with fiber glass has demonstrated being effective just in part because the capability of the fibers to transmit the strengths did not prevent the progressive collapse of the cellular structure [49]. Other studies have reported an enhancement in the mechanical properties of foamed concretes reinforced with polypropylene fibers [50]. With the use of those fibers it has been able to produce cellular concretes with  $650 \text{ kg/m}^3$  and a compressive strength of

2.7 MPa and 76.4% of the pores have a size between 0.2 and

1.0 mm [33]. Other fibers used for the reinforcement of cellular concrete are the ones that come from polyolefin, both macroscopic and fibrillated (microfibers). The structural fibers (macroscopic) induce a ductile behavior stopping the cracking propagation while the fibrillated fibers work in the micro level fissures. The best experimental results are accomplished with hybrid reinforcement but the increase in strength is not proportional with the increase in the reinforcement percentage: compressive strength increments up to 66.8% and tenacity up to 46.7% [

50]. Polyvinyl alcohol fibers also have been reported for ultra-lightweight cellular concrete reinforcement avoiding the fragile failure and augmenting tensile strength [51].

Reinforcement with latex microspheres improves the material performance acting as an energy absorption mechanism [52].

### **Foamed cellular concrete properties**

In the fresh state the mixture of foamed concrete is fluid and with self-compacting rheology. The fresh state properties consistency, stability and workability are strongly influenced by the W/C ratio, the additives and the foam type and volume [59,60].

The mixture consistency is an important factor that affects the stability. This consistency depends mainly on the type of filler [18]. In the hardened state the compressive strength with respect to density is the design property. Porosity is another property that must be taken into account because it is associated directly to the performance of a cellular concrete [9]. Pores have an important

role to enhance the insulation effect, but decreases compressive strength and elastic stiffness [61]. Porosity depends upon the type of foaming agent employed, fillers and the manufacturing process [62]. The air-entraining obviously increases the porosity of concrete [60]. Fine and close pores resulting in a compact in texture with high strength and low permeability [62]. The pores in a foamed concrete might be generated in different configurations: interlayer (<1 nm), gel (1–10 nm), capillary (>10 nm) and from suction (1–2 mm). The pore connectivity also depends on the formation methods and the type of foaming agents used [31]. Cui and Cahyadi define a critical pore diameter ( $l_c$ ) as the pore diameter above which a connected path could form throughout a sample and added that the smaller the  $l_c$ , the finer the pore structure. Hilal et al. show that in foamed concrete the critical pore diameter and the pore diameter size (>200 nm) are to be closely related to the permeability [63]. The porosity of the cellular concrete decreases as the growth of curing ages. The reason is that, the hydration degree of cement is low before 7d, which leads to higher porosity [60]. Water absorption decreases with added foam voids, suggests that these voids may not lead to an increase in water transport through foamed concrete [63]. Some methods of foam activation such as microwaves or ultrasound that lead to changes in porosity have been employed to change the internal microstructure and improve the mechanical properties [35]. The thermoacoustic isolation and the fire resistance are intrinsic properties of foamed concretes that are related to the porosity as well. The foamed concrete has sound absorption rates 10 times higher compared to a conventional concrete and thermal conductivities closer to  $0.66 \text{ W m}^{-1} \cdot \text{K}^{-1}$  [3].

About the mechanical properties Kearsley (2002) determined that the compressive strength decreases exponentially with the density reduction in foamed concretes [64]. Nevertheless, it should be highlighted that such property depends of a lot of factors: element form and size, foam production method, load path, age, water content, characteristics of mixture elements and curing process [3,46]. Kearsley also noted that for dry densities between  $500$  and  $1000 \text{ kg/m}^3$  the compressive strength reduced when the bubble diameter increases. For densities above  $1000 \text{ kg/m}^3$ , the paste composition is what controls the strength [46]. In Table 2 expected properties of foamed cellular concrete are related for different densities.

Some authors as J.M. Durack and L. Weiqing; M. Rößler and I. Odler; A.M. Neville and N. Narayanan; K.J. Byun et al. have proposed empiric models to find the compressive strength as a function of porosity, that were reported in [3]. Other models have been obtained through numerical





properties including durability. A difficulty encountered in defining foam stability criteria is the fact that very few authors specify the characteristics (commercial name or composition) of the foaming agent used, which does not allow progress in the development of more commercial mixtures.

Other important aspect to have into account is self-curing, which helps to enhance compressive strength at early age and to prevent carbonation reaction throughout the curing process [12]. Creating a source of water supply inside the concrete mixture enough for hydration process is a good idea to replace traditional superficial water addition for curing. In that sense, materials like water crystal beads can be used to supply the desired amount of water for internal hydration [76].

In the hardened state, pore internal structure is associated directly to the performance of a cellular concrete as it was shown in Section 2.3. Voids size distribution, uniformity, geometry, spatial distribution and connection are essential to understand the effect of fresh properties in the mixture (mostly foam stability) on the mechanical performance and physical properties. Despite this, volume of pores is the most useful criteria to describe the voids. Experimental works among which stand out [77,63,12], have described qualitatively internal microstructure of pores but they have not been able to introduce quantitative results for pore inter-connection or their distribution. For this reason, there is still a requirement for more deep studies that should address internal structure of cellular concretes, especially considering that factors such as the mixture design, foaming agent and curing type affect

Table 2

Cellular concrete properties with respect to density. Adapted from [13,36].

| Dry Density [kg/m <sup>3</sup> ] | Compressive Strength [MPa] | Elastic modulus [GPa] | Thermal Conductivity [W/m K] | Volumetric Contraction [%] |
|----------------------------------|----------------------------|-----------------------|------------------------------|----------------------------|
| 400                              | 0.5–1.0                    | 0.8–1.0               | 0.07–0.11                    | 0.30–0.35                  |
| 500                              | 1.0                        | 1.24–1.84             | 0.08–0.13                    | –                          |
| 600                              | 1.0–1.5                    | 2.0–2.5               | 0.11–0.17                    | 0.22–0.25                  |
| 800                              | 1.5–2.0                    | 2.0–2.5               | 0.17–0.23                    | 0.20–0.22                  |
| 1000                             | 2.5–3.0                    | 2.5–3.0               | 0.23–0.30                    | 0.15–0.18                  |
| 1200                             | 3.5–4.0                    | 3.5–4.0               | 0.38–0.42                    | 0.009–0.11                 |
| 1400                             | 6.0–8.0                    | 5.0–6.0               | 0.50–0.55                    | 0.07–0.009                 |
| 1600                             | 7.5–10.0                   | 10.0–12.0             | 0.62–0.66                    | 0.006–0.07                 |

Cellular concrete properties accepted in hardened state

|                              |          |
|------------------------------|----------|
| Physical property            | Accepted |
| Density [kg/m <sup>3</sup> ] | 400–1900 |
| Contraction [%]              | 0.1–0.35 |
| Mechanical properties        | Accepted |

Durability of cellular concrete is an important issue as well. Systematic investigations on the durability aspects of foamed concrete from a point of view based on design criteria has been already suggested by [18]. Main components of durability are mechanical strength, water absorption, frost resistance and shrinkage (including carbonation shrinkage) that rises the risk of cracking [78].

## Summary

The reviewed information shows a quick evolution of cellular concretes. The emphasis has been on creating more durable concrete with new mixtures of constituents in different proportions, whose specifications and performance are much better [5]. In recent years, the development of high-

performance cellular concretes has been achieved thanks to the use of additional binder materials. This has permitted improving the strength/weight ratio, which implies: reduction of the thickness of the structural elements, an increase of the usable interior architectural space, reduction in the amount of reinforcement, increased flexibility and minimization of the effect of temperature changes by improving energy conservation in buildings. The assessment of mechanical properties remains the central concern of researchers, as this is the foremost design condition. Aspects such as the rheology and the internal structure of the pores continue to need more development. Alternative fillers or binders, the application of nanotechnology, the discovery of new and better foaming agents and stabilizers, as well as the manufacture of geopolymeric cellular concretes are the new stakes in the study and application of foamed cellular concretes. Bigger efforts are still required in terms of process scaling and control of manufacturing conditions for the large-scale commercial exploitation of this type of concrete.

## References

1. M. Gomez, An Introduction to cellular concrete and advanced engineered foam technology, 2015.
2. J.J. Ramírez Zamora, Behavior of cellular concrete walls with different amounts of reinforcing steel (In Spanish), Universidad Nacional Autónoma de México, 2007. <<http://www.ptolomeo.unam.mx:8080/xmlui/bitstream/handle/132.248.52.100/1717/ramirezamora.pdf?sequence=1>> (accessed 22.11.17).
3. Y.H.M. Amran, N. Farzadnia, A. Abang Ali, Properties and applications of foamed concrete: a review, *Constr. Build. Mater.* 101 (2015) 990–1005, <https://doi.org/10.1016/j.conbuildmat.2015.10.112>.
4. D.K. Panesar, Cellular concrete properties and the effect of synthetic and protein foaming agents, *Constr. Build. Mater.* 44 (2013) 575–584, <https://doi.org/10.1016/j.conbuildmat.2013.03.024>.
5. S. Nandi, A. Chatterjee, P. Samanta, T. Hansda, Cellular concrete: its facets of application in civil engineering, *Int. J. Eng. Res.* (2016), <https://doi.org/10.17950/ijer/v5i1/009>.
6. A.A. Sayadi, J.V. Tapia, T.R. Neitzert, G.C. Clifton, Effects of expanded polystyrene (EPS) particles on fire resistance, thermal conductivity and compressive strength of foamed concrete, *Constr. Build. Mater.* 112 (2016) 716–724, <https://doi.org/10.1016/j.conbuildmat.2016.02.218>.
7. M.R. Jones, A. McCarthy, Heat of hydration in foamed concrete: Effect of mix constituents and plastic density, *Cem. Concr. Res.* 36 (2006) 1032–1041, <https://doi.org/10.1016/j.cemconres.2006.01.011>.
8. X. Tan, W. Chen, J. Wang, D. Yang, X. Qi, Y. Ma, X. Wang, S. Ma, C. Li, Influence of high temperature on the residual physical and mechanical properties of foamed concrete, *Constr. Build. Mater.* 135 (2017) 203–211, <https://doi.org/10.1016/j.conbuildmat.2016.12.223>.
9. N. Narayanan, K. Ramamurthy, Microstructural investigations on aerated concrete, *Cem. Concr. Res.* 30 (2000) 457–464, [https://doi.org/10.1016/S0008-8846\(00\)00199-X](https://doi.org/10.1016/S0008-8846(00)00199-X).
10. A.A. Hilal, N.H. Thom, A.R. Dawson, On entrained pore size distribution of foamed concrete, *Constr. Build. Mater.* 75 (2015) 227–233, <https://doi.org/10.1016/j.conbuildmat.2014.09.117>.
11. R.M. Ahmed, N.E. Takach, U.M. Khan, S. Taoutaou, S. James, A. Saasen, R. Godøy, Rheology of foamed cement, *Cem. Concr. Res.* 39 (2009) 353–361, <https://doi.org/10.1016/j.cemconres.2008.12.004>.
12. J. Jiang, Z. Lu, Y. Niu, J. Li, Y. Zhang, Study on the preparation and properties of high-porosity foamed concretes based on ordinary Portland cement, *Mater. Des.* 92 (2015) 949–959, <https://doi.org/10.1016/j.matdes.2015.12.068>.
13. N. Narayanan, K. Ramamurthy, Structure and properties of aerated concrete: a review, *Cem. Concr. Compos.* 22 (2000) 321–329, [https://doi.org/10.1016/S0958-9465\(00\)00016-0](https://doi.org/10.1016/S0958-9465(00)00016-0).
14. A.S. van Rooyen, Structural Lightweight Aerated Concrete, Stellenbosch University, Stellenbosch, 2013, accessed 28.11.17.
15. S.K. Lim, C.S. Tan, X. Zhao, T.C. Ling, Strength and toughness of lightweight foamed concrete with different sand grading, *KSCE J. Civ. Eng.* 19 (2015) 2191–2197, <https://doi.org/10.1007/s12205-014-0097-y>.
16. T.T. Nguyen, H.H. Bui, T.D. Ngo, G.D. Nguyen, Experimental and numerical investigation of influence of air-voids on the compressive behaviour of foamed concrete, *Mater. Des.* 130 (2017) 103–119, <https://doi.org/10.1016/j.matdes.2017.05.054>.
17. A.M. Abd, S.M. Abd, Modelling the strength of lightweight foamed concrete using support vector machine (SVM), *Case Stud. Constr. Mater.* 6 (2017) 8–15, <https://doi.org/10.1016/j.cscm.2016.11.002>.
18. K. Ramamurthy, E.K. Kunhanandan Nambiar, G. Indu Siva Ranjani, A classification of studies on properties of foam concrete, *Cem. Concr. Compos.* 31 (2009) 388–396, <https://doi.org/10.1016/j.cemconcomp.2009.04.006>.

19. E.P. Kearsley, P.J. Wainwright, The effect of high fly ash content on the compressive strength of foamed concrete, *Cem. Concr. Res.* 31 (2001) 105–112, [https://doi.org/10.1016/S0008-8846\(00\)00430-0](https://doi.org/10.1016/S0008-8846(00)00430-0).
20. S.S.Sharipudin,A.R.MohdRidzuan,R.N.H.RajaMohdNoor,A.CheHassan, Strength properties of lightweight foamed concrete incorporating waste paper sludge ash and recycled concrete aggregate, in: *Reg. Conf. Sci. Technol. Soc. Sci.* (RCSTSS 2014), Springer Singapore, Singapore, 2016, pp. 3–15, [https://doi.org/10.1007/978-981-10-0534-3\\_1](https://doi.org/10.1007/978-981-10-0534-3_1).
21. K. Jitchaiyaphum, T. Sinsiri, P. Chindaprasirt, Cellular lightweight concrete containing pozzolan materials, *Proc. Eng.* 14 (2011) 1157–1164, <https://doi.org/10.1016/j.proeng.2011.07.145>.
22. K. Gelim, I Mechanical and Physical Properties of Fly Ash Foamed Concrete, University Tun Hussein Onn Malaysia, 2011. accessed 22.11.17.
23. N. Makul, G. Sua-Iam, Characteristics and utilization of sugarcane filter cake waste in the production of lightweight foamed concrete, *J. Cleaner Prod.* 126 (2016) 118–133, <https://doi.org/10.1016/j.jclepro.2016.02.111>
24. H.Awang,Z.S.Aljoumaily,N.Noordin,The Mechanical Properties of Foamed Concrete containing Un-processed Blast Furnace Slag, *MATEC Web Conf.* 4 (2014) 1–9. doi:10.1051/mateconf/20141501034.
25. Z. Pan, H. Li, W. Liu, Preparation and characterization of super low density foamed concrete from Portland cement and admixtures, *Constr. Build. Mater.* 72 (2014) 256–261, <https://doi.org/10.1016/j.conbuildmat.2014.08.078>.
26. T. Tian, Y. Yan, Z. Hu, Y. Xu, Y. Chen, J. Shi, Utilization of original phosphogypsum for the preparation of foam concrete, *Constr. Build. Mater.* 115 (2016) 143–152, <https://doi.org/10.1016/j.conbuildmat.2016.04.028>.
27. Z. Pan, F. Hiromi, T. Wee, Preparation of high performance foamed concrete from cement, sand and mineral admixtures, *J. Wuhan Univ. Technol. Mater. Sci. Ed.* 22 (2007) 295–298, <https://doi.org/10.1007/s11595-005-2295-4>.
28. A.A. Hilal, N.H. Thom, A.R. Dawson, The use of additives to enhance properties of pre-formed foamed concrete, *Int. J. Eng. Technol.* 7 (2015) 286–293, <https://doi.org/10.7763/IJET.2015.V7.806>.
29. N.S. Ching, Potential Use of Aerated Lightweight Concrete for Energy Efficient Construction, Tunku Abdul Rahman, 2012. <<http://eprints.utar.edu.my/443/1/EGA-2012-0702914-1.pdf>> (accessed 28.11.17).
30. C.L. Hwang, V.A. Tran, A study of the properties of foamed lightweight aggregate for self-consolidating concrete, *Constr. Build. Mater.* 87 (2015) 78–85, <https://doi.org/10.1016/j.conbuildmat.2015.03.108>.
31. Z. Zhang, J.L. Provis, A. Reid, H. Wang, Geopolymer foam concrete: an emerging material for sustainable construction, *Constr. Build. Mater.* 56 (2014) 113–127, <https://doi.org/10.1016/j.conbuildmat.2014.01.081>.
32. M.M. Al Bakri Abdullah, K. Hussin, M. Bnhussain, K.N. Ismail, Z. Yahya, R.A. Razak, Fly ash-based geopolymer lightweight concrete using foaming agent, *Int. J. Mol. Sci.* 13(2012)7186–7198, <https://doi.org/10.3390/ijms13067186>.
33. O. Poznyak, A. Melnyk, Non-autoclaved aerated concrete made of modified binding composition containing supplementary cementitious materials, *Bud. i Arch.* 13 (2014) 127–134. <[http://wbia.pollub.pl/files/85/content/files/1961\\_127-134.pdf](http://wbia.pollub.pl/files/85/content/files/1961_127-134.pdf)> (accessed 22.11.17).  
A. Hajimohammadi, T. Ngo, P. Mendis, Enhancing the strength of pre-made foams for foam concrete applications, *Cem. Concr. Compos.* 87 (2018) 164–171, <https://doi.org/10.1016/J.CEMCONCOMP.2017.12.014>.
34. E. Kuzielová, L. Pach, M. Palou, Effect of activated foaming agent on the foam concrete properties, *Constr. Build. Mater.* 125 (2016) 998–1004, <https://doi.org/10.1016/j.conbuildmat.2016.08.122>.
35. K. Aini, M. Sari, A. Rahim, M. Sani, Applications of Foamed Lightweight Concrete, *MATEC Web Conf.* 97 (2017) 1–5. doi:10.1051/mateconf/20179701097.
36. D. Falliano, D. De Domenico, G. Ricciardi, E. Gugliandolo, Experimental investigation on the compressive strength of foamed concrete: effect of curing conditions, cement type, foaming agent and dry density, *Constr. Build. Mater.* 165 (2018) 735–749, <https://doi.org/10.1016/J.CONBUILDMAT.2017.12.241>.
37. C. Krämer, T. Kowald, R. Trettin, Three-phase-foams as new lightweight materials and their use in foam concretes, in: *Nanotechnol. Constr.*, Springer International Publishing, Cham, 2015, pp. 435–439, [https://doi.org/10.1007/978-3-319-17088-6\\_57](https://doi.org/10.1007/978-3-319-17088-6_57).
38. W. She, Y. Du, C. Miao, J. Liu, G. Zhao, J. Jiang, Y. Zhang, Application of organic- and nanoparticle-modified foams in foamed concrete: reinforcement and stabilization mechanisms, *Cem. Concr. Res.* 106 (2018) 12–22, <https://doi.org/10.1016/j.cemconres.2018.01.020>.
39. E.K.K. Nambiar, K. Ramamurthy, Influence of filler type on the properties of foam concrete, *Cem. Concr. Compos.* 28 (2006) 475–480, <https://doi.org/10.1016/j.cemconcomp.2005.12.001>.
40. S.K. Lim, C.S. Tan, O.Y. Lim, Y.L. Lee, Fresh and hardened properties of lightweight foamed concrete with palm oil fuel ash as filler, *Constr. Build. Mater.* 46 (2013) 39–47, <https://doi.org/10.1016/j.conbuildmat.2013.04.015>.
41. N.M. Ibrahim, S. Salehuddin, R.C. Amat, L. Rahim, T. Nuraiti, T. Izhar, Performance of lightweight foamed concrete with waste clay brick as coarse aggregate, *APCBEE Proc.* 5 (2013) 497–501, <https://doi.org/10.1016/j.apcbee.2013.05.084>.
42. A.A. Aliabdo, A.-E.M. Abd-Elmoaty, H.H. Hassan, Utilization of crushed clay brick in cellular concrete production, *Alexandria Eng. J.* 53 (2014) 119–130, <https://doi.org/10.1016/j.aej.2013.11.005>.
43. J.L. Ruiz-Herrero, D.V. Nieto, A. López-Gil, A. Arranz, A. Fernández, A. Lorenzana, S. Merino, J.A. De Saja, M. Ángel Rodríguez-Pérez, Mechanical and thermal performance of concrete and mortar cellular materials containing plastic waste, *Constr. Build. Mater. J.* 104 (2016) 298–310, <https://doi.org/10.1016/j.conbuildmat.2015.12.005>.
44. Z. Wu, B. Chen, N. Liu, Fabrication and compressive properties of expanded polystyrene foamed concrete:

- Experimental research and modeling, J. Shanghai Jiaotong Univ. 18 (2013) 61–69, <https://doi.org/10.1007/s12204-013-1369-2>.
45. Y.H. Khaw, Performance of Lightweight Foamed Concrete Using Laterite as Sand Replacement, 2010.doi:10.1017/CBO9781107415324.004.
46. Y. Yang, B. Chen, Potential use of soil in lightweight foamed concrete, KSCE J.Civ. Eng. 20 (2016) 2420–2427, <https://doi.org/10.1007/s12205-016-0140-2>.
47. Q. AbdSaloum, M. Zaid Abdullah, A. Adnan Hashim, The preparation of foam cement and determining some of its properties, Eng. Technol. J. 33 (2015) 61–69.
48. F. Akthar, J.R. Evans, High porosity (>90%) cementitious foams, Cem. Concr.Res. 40 (2010) 352–358, <https://doi.org/10.1016/J.CEMCONRES.2009.10.012>.
49. M. Abdur Rasheed, S. Suriya Prakash, Mechanical behavior of sustainable hybrid-synthetic fiber reinforced cellular lightweight concrete for structural applications of masonry, Constr. Build. Mater. 98 (2015) 631–640, <https://doi.org/10.1016/J.CONBUILDMAT.2015.08.137>.
51. J.B. Yan, J.Y. Wang, J.Y.R. Liew, X. Qian, Applications of ultra-lightweight cement composite in flat slabs and double skin composite structures, Constr. Build. Mater. 111 (2016) 774–793, <https://doi.org/10.1016/j.conbuildmat.2016.02.122>.
52. G. Li, V.D. Muthyala, A cement based syntactic foam, Mater. Sci. Eng. A. 478 (2008) 77–86, <https://doi.org/10.1016/j.msea.2007.05.084>.
53. I.K. Harith, Study on polyurethane foamed concrete for use in structural applications, Case Stud. Constr. Mater. 8 (2018) 79–86, <https://doi.org/10.1016/J.CSCM.2017.11.005>.
54. Z. Huang, T. Zhang, Z. Wen, Proportioning and characterization of Portland cement-based ultra-lightweight foam concretes, Constr. Build. Mater. 79 (2015) 390–396, <https://doi.org/10.1016/j.conbuildmat.2015.01.051>.
55. F. Falade, B. Ukponu, The Potential of Laterite as Fine Aggregate in Foamed Concrete Production, 3 (2013). [www.iiste.org](http://www.iiste.org) (accessed August 9, 2018).
56. T.J. Chandni, K.B. Anand, Utilization of recycled waste as filler in foam concrete, J. Build. Eng. 19 (2018) 154–160, <https://doi.org/10.1016/J.JOBE.2018.04.032>.
57. M. Cong, C. Bing, Properties of a foamed concrete with soil as filler, Constr. Build. Mater. 76 (2015) 61–69, <https://doi.org/10.1016/j.conbuildmat.2014.11.066>.
58. Y. Xie, J. Li, Z. Lu, J. Jiang, Y. Niu, Effects of bentonite slurry on air-void structure and properties of foamed concrete, Constr. Build. Mater. 179 (2018) 207–219, <https://doi.org/10.1016/j.conbuildmat.2018.05.226>.
59. Y.H.M. Amran, A.A.A. Ali, R.S.M. Rashid, F. Hejazi, N.A. Safiee, Structural behavior of axially loaded precast foamed concrete sandwich panels, Constr. Build. Mater. 107 (2016) 307–320, <https://doi.org/10.1016/j.conbuildmat.2016.01.020>.
60. Y. Li, W. Dong, H. Li, Z. Li, Method of vacuum water absorption to determine the porosity of hardened concrete, Int. J. Struct. Civ. Eng. Res. 4 (2015) 282–286, <https://doi.org/10.18178/ijscer.4.3.282-286>.
61. S.-Y. Chung, C. Lehmann, M. Abdelrahman, D. Stephan, Pore characteristics and their effects on the material properties of foamed concrete evaluated using micro-CT images and numerical approaches, Appl. Sci. 7 (2017) 550, <https://doi.org/10.3390/app7060550>.
62. X.G. Yu, S.S. Luo, Y.N. Gao, H.F. Wang, Y.X. Li, Y.R. Wei, X.J. Wang, Pore structure and microstructure of foam concrete, Adv. Mater. Res. 177 (2010) 530–532, <https://doi.org/10.4028/www.scientific.net/AMR.177.530>.
63. A.A. Hilal, N.H. Thom, A.R. Dawson, Pore structure and permeation characteristics of foamed concrete, J. Adv. Concr. Technol. 12 (2014) 535–544, <https://doi.org/10.3151/jact.12.535>.
64. P. Kearsley, E.P. Wainwright, Effect of porosity on the strength of concrete, Cem. Concr. Res. 32 (2002) 233–239.
65. A.O. Mydin, Y.C. Wang, An exptemperatures up to 600 °C, Concr. Res. Lett. 1 (2010) 142–157. accessed 30.01.18.
66. M.A.O. Mydin, Y.C. Wang, Mechanical properties of foamed concrete exposed to high temperatures, Constr. Build. Mater. 26 (2012) 638–654, <https://doi.org/10.1016/j.conbuildmat.2011.06.067>.
67. Lcc, High strength structural lightweight concrete, 2003. <<http://www.lightconcrete.com/images/lightconcrete.pdf>> (accessed 22.11.17).
68. S.-J. Ma, E.-G. Kang, D.-M. Kim, The study on development of light-weight foamed mortar for tunnel backfill, Adv. Mater. Dev. Perform. Int. J. Mod. Phys. Conf. Ser. 6 (2011) 449–454, <https://doi.org/10.1142/S2010194512003595>.
69. H. Wang, W. Chen, X. Tan, H. Tian, J. Cao, Development of a new type of foam concrete and its application on stability analysis of large-span soft rock tunnel, J. Cent. South Univ. 19 (2012) 3305–3310, <https://doi.org/10.1007/s11771-012-1408-4>.
70. B. Tiwari, B. Ajmera, R. Maw, R. Cole, D. Villegas, P. Palmerson, Mechanical properties of lightweight cellular concrete for geotechnical applications, J. Mater. Civ. Eng. 29 (2017) 06017007, [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0001885](https://doi.org/10.1061/(ASCE)MT.1943-5533.0001885).
71. J. Jie Huang, Q. Su, W. Hui Zhao, T. Li, X. Xi Zhang, Experimental study on use of lightweight foam concrete as subgrade bed filler of ballastless track, Constr. Build. Mater. 149 (2017) 911–920,



- <https://doi.org/10.1016/j.conbuildmat.2017.04.122>.
72. H.-S.Lee,M.Ismail,Y.-J.Woo,T.-B.Min,H.-K.Choi,FundamentalStudyonthe Development of Structural Lightweight Concrete by Using Normal Coarse Aggregate and Foaming Agent, *Materials (Basel)*. 7 (2014) 4536–4554, <https://doi.org/10.3390/ma7064536>.
  73. N. Mustapure, H. Eramma, Experimental investigation on cellular lightweight concrete blocks for varying grades of density, *Int. J. Adv. Technol. Eng. Sci.*, *Www.Ijates.Com*. (2014) 2348–7550. <[http://ijates.com/images/short\\_pdf/1407002401\\_P10-18.pdf](http://ijates.com/images/short_pdf/1407002401_P10-18.pdf)> (accessed22.11.17).
  74. Y.H.M. Amran, R.S. Rashid, F. Hejazi, N.A. Safiee, A.A.A. Ali, Response of precast foamed concrete sandwich panels to flexural loading, *J. Build. Eng.* 7 (2016) 143–158,<https://doi.org/10.1016/j.jobe.2016.06.006>.
  75. K.-K. Yun, N. Kyong, S.-Y. Han, K.-R. Lee, Cellular sprayed concrete: a very- simple and economic method for remixing and OPC into HPC at a field, in: D.A.Hordijk,M.Luković,(Eds.),*HighTechConcr.WhereTechnol.Eng.MeetProc.2017 Fib Symp.*,Springer International Publishing, 2017, pp.132–139.
  76. N. Salim, T. Dhirar, Production of High Performance Cellular Concrete Using Water Crystal Beads, AL-Taqani. (2011) 154–165. <<https://www.iasj.net/iasj?func=fulltext&aId=28302>> (accessed3.12.18).Just, B. Middendorf, Microstructure of high-strength foam concrete, *Mater. Charact.*60(2009)741–748,<https://doi.org/10.1016/j.matchar.2008.12.011>.
  77. E. Namsone, G. Šahmenko, A. Korjakins, Durability properties of high performance foamed concrete, *Proc. Eng.* (2017) 760–767, <https://doi.org/10.1016/j.proeng.2017.02.120>.
  78. erimental investigation of mechanical propertiesof lightweight foamed concrete subjected toelevated

