Waste as Cement Replacement in Foamed Concrete

Subjects: Engineering, Civil

Contributor: Rokiah Othman, Ramadhansyah Putra Jaya, Youventharan Duraisamy, Mohd Arif Sulaiman, Beng Wei Chong, Ali Ghamari

Foamed concrete is a lightweight construction material that has gained popularity due to its excellent thermal and acoustic insulation properties. Foamed concrete production involves using cement as a binding agent, which results in a high carbon footprint. In response to sustainable development goals (SDG), there has been a growing interest in exploring alternative materials that can replace cement to improve energy efficiency, climate change, resource efficiency, and overall improvement of foamed concrete properties.

Keywords: efficiency ; industrials waste ; cement replacement ; foamed concrete

1. Introduction

The growth of industrial activities has led to the generation of significant amounts of waste, known as industrial waste (IW). Most industries are unable to reuse these wastes due to their low value and higher cost [1]. In response to sustainable development goals (SDG), the construction sector has the potential to reuse large volumes of IW as they annually consume large volumes of materials such as cement, aggregates, sand, blocks, bricks, and tiles for the development of new buildings and projects. Additionally, the reuse of IW may lead to sustainable construction as the production of materials for buildings and projects consumes large volumes of natural raw materials and energy [2]. Globally, pozzolanic alternative (PA) materials are frequently used in construction as partial replacements for ordinary Portland cement (OPC) in mortar and concrete.

One of the most acceptable types of PA is pozzolanic waste material because of its environmental benefits during the production of OPC. The construction industry is one of the primary sectors facing the challenges of energy, climate change, and resource efficiency. Concrete is the most commonly used material in the construction industry due to its strength and durability, but its production has a negative impact on the environment. The world is facing the major challenge of producing more than 10 billion tons of concrete every year, which requires billions of tons of material to produce. OPC is a critical component of concrete, but its production has led to the generation of higher carbon dioxide emissions. Globally, the production of one ton of OPC releases one ton of CO_2 from the calcination of limestone [3][4].

In Malaysia, the annual production of 20 million tons of cement leads to the release of 20 million tons of CO_2 into the atmosphere [5]. It is estimated that approximately 7% of CO_2 is recognized as a greenhouse gas that contributes to global warming [3]. Therefore, utilizing pozzolanic material is one solution for reducing the amount of cement used in construction [6]. Foamed concrete (FC) is an eco-friendly and economical type of concrete that incorporates pozzolan alternatives as a partial cement replacement in an FC mixture. Several pozzolan materials, such as fly ash, silica fume, ground granulated blast furnace slag (GGBS), and rice husk ash (RHA), have been used effectively as partial cement replacements due to their ability to reduce greenhouse gas (GHG) emissions. FC is a mixture of cement paste and preformed foams that provides cost savings, ease of handling, is self-compacting, and lower density [7][8][9]. Any supplementary cementitious material or pozzolans can be used as sand or cement in FC, making it an attractive alternative to traditional concrete [10][11]. PA from industrial by-products or waste (IW) can also be used as a replacement for cement in FC, such as RHA [12], fly ash [13][14], silica fume [15], GGBS [16], sewage sludge ash [17], paper mill sludge [18], graphite tailing [19][20], palm oil fuel ash [21][22], and soil as a sand replacement [23].

Recent studies have explored the use of various waste materials in FC production, such as sugarcane bagasse ash (SCBA), rubber glove (RG), and waste glass powder (WGP). A study by Li et al. [24] investigated the effect of SCBA on the properties of FC and found that SCBA can be used as a partial replacement for sand in FC production to enhance its properties. Another study by Hameed et al. [25] explored the use of RV and WGP as a pozzolanic material in FC production and found that it significantly improved the compressive strength, workability, and durability of FC. Similarly, a study by Khan et al. [26] examined the use of WGP as a pozzolanic material in FC production and found that it can improve the mechanical properties of FC. Overall, the studies share similar findings, PA in FC enhances its long-term strength, durability, and microstructure. It is economical and eco-friendly as it reduces greenhouse gas emissions, including carbon dioxide, and reuses industrial waste while minimizing cement usage. In addition, the studies highlight the potential for using different types of waste as replacement materials for cement in FC production and the need for further research in this area to identify the most efficient types of waste to develop more sustainable and high-performance FC.

However, the properties of foamed concrete are highly dependent on the mix design parameters, which can make it challenging to predict the compressive strength and rheological properties of FC. Researchers have been investigating the effects of mixed design parameters on foamed concrete properties and using statistical analysis to identify correlations between these parameters and the strength and rheology of the material. Dao et al. [27] used a statistical approach to optimize the mix proportions of foamed concrete and identified correlations between the dry density, water-cement ratio, foam content, sand content, and the compressive strength of the foamed concrete. The compressive strength of FC decreased when the water-cement and sand-cement ratios increased. However, the study found that dry density positively affected compressive strength with a maximum R^2 value of 0.976. A study by Calis et al. [28] investigated the effects of ground calcium carbonate and glass fiber on the compressive and flexural strength and thermal conductivity of foamed concrete and found that the compressive strength and thermal conductivity were positively correlated with the amount of ground calcium carbonate. Additionally, the inclusion of glass fiber in the mix design contributes to the flexural strength of FC. Similarly, a study by Ullah et al. [29] investigated the influence of cement content, sand content, water-cement ratio, and foam volume on the dry density and compressive strength of FC. The study identified strong correlations of R^2 0.95 between the dry density and compressive strength of FC with the least statistical errors, 2% for the density model, and 91% of the predicted results have error values less than 5 MPa for the strength model. Overall, these recent studies demonstrate the importance of mixed design parameters in determining the compressive strength of the foamed concrete were positively correlated with the cement content and foam content and negatively correlated with the water-cement ratio and sand content. The foamed concrete's rheological properties highly depended on the water-cement ratio and foam content.

As per the ACI 232.1R-00 report by the American Concrete Institute (ACI), a pozzolan is a siliceous and aluminous material that reacts with calcium hydroxide (lime) from cement to create a secondary calcium silicate hydrate (CSH) gel [30]. Pozzolan, in itself, possesses little or no cementitious properties, but in finely divided form and in the presence of moisture, it significantly improves the workability, compressive strength, and durability of concrete [31][32][33][34][35][36][37][38][39]. The Greeks and Romans have used natural pozzolan to construct some of their most impressive buildings, and the pozzolanic reaction occurs when silica (S) reacts with calcium hydroxide (CH) and water (W) to produce additional calcium silicate hydrate (CSH) gel. The reactivity of pozzolan is dependent on its specific surface area, mineralogical composition, and reactive silica content. It's remarkable to see how something as seemingly simple as pozzolan can contribute to the creation of such impressive and long-lasting structures. The pozzolanic reaction happens during the hydration process as is shown in Equation (1) [40].

$$\mathrm{S + CH + H \;\rightarrow\; C - S - H} \tag{1}$$

It is important to highlight that the characteristics of the waste generated depend on the technologies used by the industries, and as such, some IW is generated from the combustion process, such as fly ash and bottom ash, which have pozzolanic properties. Growing environmental concerns over the disposal of industrial by-products combined with carbon dioxide emissions during the OPC clinker's burning process have led to increased usage of pozzolan ash as a replacement material for cement. The efficient use of resources through using pozzolan alternatives as a replacement for industrial by-products or waste could reduce environmental issues and costs due to the high demand for OPC.

2. The Characterization Process of Waste

The ASTM C618-19 standard recognizes two classes of ash, which are Class C ash and Class F ash. Pozzolan materials are distinguished based on the sum of the oxides of silicon, aluminum, and iron (SAF). If the SAF is found to be less than 70%, the pozzolan material is classified as Class C ash and if SAF is more than 70%, the pozzolan material is classified as Class F ash. In Europe, there are also several standards that classify ash based on different classes, as well as the use of ashes in materials with a cement binder. One such standard is the EN 450 standard, which categorizes fly ash into three different classes: Class N, Class S, and Class P. This standard defines the classes based on the sum of the oxides of silicon, aluminum, and iron (SAI) rather than SAF, as in the ASTM C618-19 standard. Additionally, the EN 450 standard considers the chemical composition, mineralogy, and pozzolanic activity of the fly ash to determine its class. Another European standard that addresses the use of ashes in materials with a cement binder is the EN 197-1 standard. This standard defines five different types of cement, including Portland cement, and allows for the partial replacement of Portland cement with fly ash or other pozzolanic materials. The standard also includes requirements for the physical and chemical properties of these materials. This present research reviewed the properties of a pozzolan alternative (PA) as a partial replacement for cement based on the ASTM C618-19 standard. The research evaluated the efficiency of the PA to enhance the properties of FC, with the pozzolanic reaction forming additional calcium silicate hydrate (CSH) gel and improving the strength and durability of the FC. The research also established criteria for the chemical and physical properties of the PA, such as a specific surface area, silica content, and particle size. Finally, the research aimed to investigate the strength development of FC through the replacement of cement with PA, and aimed to provide more than 75% strength compared to the control at 28 days according to the EN 450 standard. By incorporating a pozzolan alternative as a cement replacement, the research suggests that waste materials can be utilized, and CO_2 emissions can be reduced while conserving energy and resources.

In the world of construction, finding the perfect materials for a project can mean the difference between success and failure. When it comes to evaluating and characterizing industrial waste (IW) for use as a pozzolan material in construction, the first stage of evaluation is crucial. Processed spent bleaching earth (PSBE) is the end product derived from the processing of de-oiled SBE after the oil is recovered. Bleaching earth is very fine powder clay, and its main component is silicon dioxide, which is used for the refining process of palm oil. Its by-product is known as spent bleaching earth (SBE) and is commonly disposed in landfills at a high cost. The availability of SBE due to its consistent disposal from palm oil mills could be explored to determine its potential for material production rather than dumping it as waste. This stage involves examining the chemical and physical properties of the IW. Chemical analysis obtained by XRF is one key factor that determines the success of the pozzolanic reaction indicating that the amount of SAF should be more than 70%. The mineral form, obtained by the XRD test, is another essential compound that must be evaluated. In addition to the chemical properties, the physical properties of the pozzolan material must also be characterized, including fineness, high specific surface area, and particle size (<45 um) with more than 60% of particles in this size range. After the chemical and physical properties have been evaluated, the next stage is to assess the pozzolanic reactivity of the IW when it reacts with lime. The final stage is to investigate the strength development of the FC by replacing cement with pozzolan material. This replacement should result in more than 75% strength compared to the control at 28 days, according to the EN 450 standard. It is important to note that the effectiveness of the pozzolan material in converting calcium hydroxide (CH) to calcium silicate hydrate (CSH) gel depends on its amorphous state, silica content, and specific surface area. Higher surface areas lead to higher adsorption of chemical substances and improved pozzolanic reaction. This reaction, in turn, creates additional CSH gel that improves the properties of the foamed concrete by creating a denser microstructure. The denser structure fills larger spaces and reduces the size of capillary voids, ultimately leading to better strength and durability. With proper evaluation and characterization, IW can become an invaluable resource for sustainable construction practices.

3. Compressive Strength of FC with Pozzolan Alternatives

The compressive strength of FC is an important factor in determining its suitability for various applications. In order to determine the compressive strength of FC, 100 mm cubes were tested using a universal testing machine (UTM) in accordance with ASTM C513-11 [41]. The compressive strength of FC is affected by a variety of factors such as density, age, curing method, and mix proportion components. The base mix and foam used also play a role in determining the compressive strength of FC [42]. Previous studies have found that the compressive strength of FC with densities ranging from 800–1000 kg/m^3 is between 1–8 N/mm^2, which is adequate for its intended purposes such as void filling, highway reinstatement, and other underground works [43]. If FC is to be used for structural applications, however, a compressive strength of at least 25 N/mm^2 is necessary [44]. The compressive strength of FC is influenced by various factors, including density, cement type and content, pozzolan alternative material type and content, water-cement ratio, foaming agent type, and curing regimes [45][46][47]. The relationship between compressive strength and dry density was reported by [48], which found that an increase in density results in an increase in compressive strength. The water content of the mixes also significantly affects the compressive strength of FC. It has been found that compressive strength increases with the use of a suitable water content [49]. In addition, the compressive strength of FC increases with time. It has also been found that the optimum ash/cement ratio increases with increasing age. These findings suggest that the use of suitable mix proportions, curing methods, and pozzolan alternative materials can contribute to the densification of the concrete internal structure through the pozzolanic reaction, resulting in an increase in compressive strength of FC.

According to [50], the compressive strength of normal concrete increases with higher cement content, and this pattern is similar in FC. However, [51] reported that the strength increase is minimal above a cement content of 500 kg/m^3. In addition to cement, the use of PA such as fly ash, GGBS, silica fume, and POFA also influences the compressive strength and other properties of FC. Zhang et al. [52] found that fly ash can be used to achieve an ultimate strength of more than 50 MPa in higher density FC at 1500 kg/m^3. Similarly, a study by [53][54] reported that high calcium fly ash can increase the compressive strength of FC, and the optimal fly ash content for maximum strength after one year is nearly 60% of the cementitious material content. The type of foaming agent used also affects the compressive strength of FC, with protein-based foams increasing the strength through the creation of a closed cell network. It is important to note that when comparing the properties of FC, only mixes with the same type of foaming agents should be examined [7][54]. The foaming agent's dilution ratio also has a significant impact on the compressive strength and flexural strength of FC [55], with an optimal dilution ratio of 1:60. Additionally, the foam dosage should be carefully determined during the pre-formed foam stage, as the variation of foam dosage can affect the plastic density and, thus, the compressive strength of FC.

4. Water Absorption of FC with Pozzolan Alternatives

Water absorption is an important characteristic of concrete, as it reflects the ability of the material to absorb water. It is typically expressed as the percentage of the absorbed water to the dry mass of the specimen and is determined by measuring the specimen's constant mass, immersing it in water, and measuring the increase in mass as a percentage of dry mass. There are various methods used to measure water absorption, including 24 h immersion in water, immersion until constant mass is achieved, and vacuum saturation. However, it is important to note that different methods can produce widely different results. According to ASTM C642-13 [56], water absorption is the test used to determine the relative water absorption by the capillary uptake characteristic of mortar. In general, the water absorbed by oven-dried specimens is measured after a 48 h of immersion, or after such immersion followed by 5 h in boiling water. The ratio of the water absorbed to the dry weight is the absorption. Capillary absorption is not only affected by the water-cement ratio, but also by the paste content in the mix. As the paste content increases, the absorption also increases, and the effect is more pronounced for higher water-cement ratios [57]. It has been observed that FC has a higher water absorption value than normal concrete. The volume of water absorbed by FC is twice that absorbed by a cement paste with a similar water-cement ratio. However, the volume of water absorbed by FC appears to be insignificantly influenced by the volume of air entrained. The water absorption per unit volume of cement paste increases with increasing porosity [13]. In addition, research on other materials such as bentonite and pozzolan has shown that the water absorption rate can be influenced by factors such as the amount of the material, the curing period, and the density of the material [58][59]. Furthermore, the water absorption rate can also affect the compressive strength of the specimen. Lower water absorption rates tend to result in better compressive strength. The rate of water absorption in FC with fly ash reduces with time and becomes constant within 7 days [60]. Additionally, it is noted that water absorption decreases with increasing foam volume because the entrained pores are not interconnected. It is observed that the water absorption decreases with decreased porosity. Furthermore, the water absorption slightly increases with increased density. A study by [61][62] reported that the water absorption of a specimen produced by FC with PSBE was about 52% lower than FC produced with OPC. The positive effect of PSBE in FC is due to the decrease in the interconnected pore structure that leads to a decrease in the water absorption. Hence, only the capillary pores contribute to water absorption, which depends on the hydrated paste [63].

References

1. Chinda, T. Investigation of factors affecting a construction waste recycling decision. Civ. Eng. Environ. Syst. 2016, 33, 214–226.
2. Breuer, A.; Janetschek, H.; Malerba, D. Translating Sustainable Development Goal (SDG) Interdependencies into Policy Advice. Sustainability 2019, 11, 2092.
3. Durastanti, C.; Moretti, L. Environmental Impacts of Cement Production: A Statistical Analysis. Appl. Sci. 2020, 10, 8212.
4. Rafiza, A.R.; Fazlizan, A.; Thongtha, A.; Asim, N.; Noorashikin, M.S. The Physical and Mechanical Properties of Autoclaved Aerated Concrete (AAC) with Recycled AAC as a Partial Replacement for Sand. Buildings 2022, 12, 60.
5. Bakhtyar, B.; Kacemi, T.; Nawaz, M.A. A Review on Carbon Emissions in Malaysian Cement Industry. Int. J. Energy Econ. Policy 2017, 7, 282–286.
6. Li, G.; Zhou, C.; Ahmad, W.; Usanova, K.I.; Karelina, M.; Mohamed, A.M.; Khallaf, R. Fly Ash Application as Supplementary Cementitious Material: A Review. Materials 2022, 15, 2664.
7. Oginni, F.A. Continental Appplication of Foamed Concrete Technology: Lessons for Infrastructural Development in Africa. Br. J. Appl. Sci. Technol. 2015, 5, 417.
8. Chica, L.; Alzate, A. Cellular concrete review: New trends for application in construction. Constr. Build. Mater. 2019, 200, 637–647.

9. Amran, M.; Huei Lee, Y.; Vatin, N.; Fediuk, R.; Poi-Ngian, S.; Yong Lee, Y.; Murali, G. Design Efficiency, Characteristics, and Utilization of Reinforced Foamed Concrete: A Review. Crystals 2020, 10, 948.
10. Yang, D.; Liu, M.; Zhang, Z.; Yao, P.; Ma, Z. Properties and Modification of Sustainable Foam Concrete Including Eco-friendly Recycled Powder From Concrete Waste. Case Stud. Constr. Mater. 2022, 16, e00826.
11. Richard, A. Experimental Production of Sustainable Lightweight Foamed Concrete. Br. J. Appl. Sci. Technol. 2013, 3, 994–1005.
12. Bayuaji, R. The Influence of Microwave Incinerated Rice Husk Ash on Foamed Concrete Workability and Compressive Strength Using Taguchi Method. J. Teknol. 2015, 75, 265–274.
13. She, W.; Du, Y.; Zhao, G.; Feng, P.; Zhang, Y.; Cao, X. Influence of coarse fly ash on the performance of foam concrete and its application in high-speed railway roadbeds. Constr. Build. Mater. 2018, 170, 153–166.
14. Chen, Y.G.; Guan, L.L.; Zhu, S.Y.; Chen, W.J. Foamed concrete containing fly ash: Properties and application to backfilling. Constr. Build. Mater. 2021, 273, 121685.
15. Bing, C.; Zhen, W.; Ning, L. Experimental Research on Properties of High-Strength Foamed Concrete. J. Mater. Civ. Eng. 2012, 24, 113–118.
16. Awang, H.; Mydin, A.O.; Roslan, A.F. Microstructural Investigation of Lightweight Foamed Concrete Microstructural Investigation of Lightweight Foamed. Int. J. Acad. Res. 2012, 4, 196–200.
17. Donatello, S.; Cheeseman, C.R. Recycling and recovery routes for incinerated sewage sludge ash (ISSA): A review. Waste Manag. 2013, 33, 2328–2340.
18. Sharipudin, S.S.; Ridzuan, A.R.M. Influence of waste paper sludge ash (WPSA) and fine recycled concrete aggregate (FRCA) on the compressive strength characteristic of foamed concrete. Adv. Mater. Res. 2013, 626, 376–380.
19. Tan, X.; Han, F.; Zhao, F. Preparation of autoclaved foamed concrete block from fly ash and carbide slag. MATEC Web Conf. 2018, 142, 02006.
20. Peng, Y.; Liu, Y.; Zhan, B.; Xu, G. Preparation of autoclaved aerated concrete by using graphite tailings as an alternative silica source. Constr. Build. Mater. 2021, 267, 121792.
21. Lim, S.K.; Tan, C.S.; Lim, O.Y.; Lee, Y.L. Fresh and hardened properties of lightweight foamed concrete with palm oil fuel ash as filler. Constr. Build. Mater. 2013, 46, 39–47.
22. Alengaram, U.J.; Al Muhit, B.A.; bin Jumaat, M.Z.; Jing, M.L.Y. A comparison of the thermal conductivity of oil palm shell foamed concrete with conventional materials. Mater. Des. 2013, 51, 522–529.
23. Cong, M.; Bing, C. Properties of a foamed concrete with soil as filler. Constr. Build. Mater. 2015, 76, 61–69.
24. Li, Y.; Chai, J.; Wang, R.; Zhang, X.; Si, Z. Utilization of sugarcane bagasse ash (SCBA) in construction technology: A state-of-the-art review. J. Build. Eng. 2022, 56, 104774.
25. Hameed, A.M.; Hamada, R.F. Using the glass and rubber waste as sustainable materials to prepare foamed concrete with improved properties. IOP Conf. Ser. Mater. Sci. Eng. 2020, 881, 012188.
26. Khan, Q.S.; McCarthy, T.J.; Sheikh, M.N. Experimental investigations of foamed concrete with recycled waste glass powder wall panels. Struct. Concr. 2022, 23, 3929–3944.
27. Dao, D.V.; Ly, H.-B.; Vu, H.-L.T.; Le, T.-T.; Pham, B.T. Investigation and Optimization of the C-ANN Structure in Predicting the Compressive Strength of Foamed Concrete. Materials 2020, 13, 1072.
28. Calis, G.; Yildizel, S.A.; Erzin, S.; Tayeh, B.A. Evaluation and optimisation of foam concrete containing ground calcium carbonate and glass fibre (experimental and modelling study). Case Stud. Constr. Mater. 2021, 15, e00625.
29. Ullah, H.S.; Khushnood, R.A.; Ahmad, J.; Farooq, F. Predictive modelling of sustainable lightweight foamed concrete using machine learning novel approach. J. Build. Eng. 2022, 56, 104746.
30. ASTM C618-19; Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. ASTM International: West Conshohocken, PA, USA, 2013.
31. Ahmad, S.; Al-Amoudi, O.S.B.; Khan, S.M.; Maslehuddin, M. Effect of silica fume inclusion on the strength, shrinkage and durability characteristics of natural pozzolan-based cement concrete. Case Stud. Constr. Mater. 2022, 17, e01255.
32. Hossain, M.M.; Karim, M.R.; Hasan, M.; Hossain, M.K.; Zain, M.F.M. Durability of mortar and concrete made up of pozzolans as a partial replacement of cement: A review. Constr. Build. Mater. 2016, 116, 128–140.
33. K Al-Chaar, G.; Alkadi, M.; Asteris, P.G. Natural Pozzolan as a Partial Substitute for Cement in Concrete. Open Constr. Build. Technol. J. 2013, 7, 33–42.

34. Nwankwo, C.O.; Bamigboye, G.O.; Davies, I.E.; Michaels, T.A. High volume Portland cement replacement: A review. Constr. Build. Mater. 2020, 260, 120445.

35. Nasir, M.; Al-Amoudi, O.S.B.; Maslehuddin, M. Effect of placement temperature and curing method on plastic shrinkage of plain and pozzolanic cement concretes under hot weather. Constr. Build. Mater. 2017, 152, 943–953.

36. Dedeloudis, C.; Zervaki, M.; Sideris, K.; Juenger, M.; Alderete, N.; Kamali-Bernard, S.; Snellings, R. Natural pozzolans. In Properties of Fresh and Hardened Concrete Containing Supplementary Cementitious Materials: State-of-the-Art Report of the RILEM Technical Committee 238-SCM; Springer: Berlin/Heidelberg, Germany, 2018; Volume 4, pp. 181–231.

37. Zhou, Y.; Wang, Z.; Zhu, Z.; Chen, Y.; Wu, K.; Huang, H.; Xu, L. Influence of metakaolin and calcined montmorillonite on the hydration of calcium sulphoaluminate cement. Case Stud. Constr. Mater. 2022, 16, e01104.

38. Danner, T.; Norden, G.; Justnes, H. Characterisation of calcined raw clays suitable as supplementary cementitious materials. Appl. Clay Sci. 2018, 162, 391–402.

39. Valipour, M.; Pargar, F.; Shekarchi, M.; Khani, S. Comparing a natural pozzolan, zeolite, to metakaolin and silica fume in terms of their effect on the durability characteristics of concrete: A laboratory study. Constr. Build. Mater. 2013, 41, 879–888.

40. McCarthy, M.J.; Dyer, T.D. Pozzolanas and pozzolanic materials. Lea's Chem. Cem. Concr. 2019, 5, 363–467.

41. ASTM C513/C513M; Standard Test Method for Obtaining and Testing Specimens of Hardened Lightweight Insulating Concrete for Compressive Strength. ASTM International: West Conshohocken, PA, USA, 2011.

42. Fu, Y.; Wang, X.; Wang, L.; Li, Y. Foam concrete: A state-of-the-art and state-of-the-practice review. Adv. Mater. Sci. Eng. 2020, 2020, 6153602.

43. Raj, A.; Sathyan, D.; Mini, K.M. Physical and functional characteristics of foam concrete: A review. Constr. Build. Mater. 2019, 221, 787–799.

44. Amran, Y.M.; Rashid, R.S.; Hejazi, F.; Safiee, N.A.; Ali, A.A. Response of precast foamed concrete sandwich panels to flexural loading. J. Build. Eng. 2016, 7, 143–158.

45. Li, G.; Tan, H.; He, X.; Zhang, J.; Deng, X.; Zheng, Z.; Guo, Y. The influence of wet ground fly ash on the performance of foamed concrete. Constr. Build. Mater. 2021, 304, 124676.

46. Lee, Y.L.; Tan, C.S.; Lim, S.K.; Mohammad, S.; Lim, J.H. Strength performance on different mix of cement-sand ratio and sand condition for lightweight foamed concrete. E3S Web Conf. 2018, 65, 02006.

47. Kursuncu, B.; Gencel, O.; Bayraktar, O.Y.; Shi, J.; Nematzadeh, M.; Kaplan, G. Optimization of foam concrete characteristics using response surface methodology and artificial neural networks. Constr. Build. Mater. 2022, 337, 127575.

48. Jones, M.R.; Ozlutas, K.; Zheng, L. High-volume, ultra-low-density fly ash foamed concrete. Mag. Concr. Res. 2017, 69, 1146–1156.

49. Song, Y.; Lange, D. Influence of fine inclusions on the morphology and mechanical performance of lightweight foam concrete. Cem. Concr. Compos. 2021, 124, 104264.

50. Juenger, M.C.; Siddique, R. Recent advances in understanding the role of supplementary cementitious materials in concrete. Cem. Concr. Res. 2015, 78, 71–80.

51. Allouzi, R.; Al Qatawna, A.; Al-Kasasbeh, T. Lightweight Foamed Concrete Mixture for Structural Use. ACI Mater. J. 2020, 117, 99–109.

52. Zhang, S.; Qi, X.; Guo, S.; Zhang, L.; Ren, J. A systematic research on foamed concrete: The effects of foam content, fly ash, slag, silica fume and water-to-binder ratio. Constr. Build. Mater. 2022, 339, 127683.

53. Falliano, D.; De Domenico, D.; Ricciardi, G.; Gugliandolo, E. Experimental investigation on the compressive strength of foamed concrete: Effect of curing conditions, cement type, foaming agent and dry density. Constr. Build. Mater. 2018, 165, 735–749.

54. Amran, Y.M.; Farzadnia, N.; Ali, A.A. Properties and applications of foamed concrete; a review. Constr. Build. Mater. 2015, 101, 990–1005.

55. Yu, X.G.; Luo, S.S.; Gao, Y.N.; Xiao, H.; Li, D.J.; Xu, H.C.; Li, F. Microstructure, Mineral Phases and Strength of the Foam Concrete. Key Eng. Mater. 2011, 492, 484–488.

56. ASTM C642-13; Standard Test Method for Density, Absorption, and Voids in Hardened Concrete. ASTM International: West Conshohocken, PA, USA, 2013.

57. Zhao, H.; Ding, J.; Huang, Y.; Tang, Y.; Xu, W.; Huang, D. Experimental analysis on the relationship between pore structure and capillary water absorption characteristics of cement-based materials. Struct. Concr. 2019, 20, 1750–1762.

58. Liu, M.; Hu, Y.; Lai, Z.; Yan, T.; He, X.; Wu, J.; Lv, S. Influence of various bentonites on the mechanical properties and impermeability of cement mortars. Constr. Build. Mater. 2020, 241, 118015.

59. Ahmad, J.; Kontoleon, K.J.; Al-Mulali, M.Z.; Shaik, S.; El Ouni, M.H.; El-Shorbagy, M.A. Partial Substitution of Binding Material by Bentonite Clay (BC) in Concrete: A Review. Buildings 2022, 12, 634.

60. Mehta, A.; Siddique, R. Sulfuric acid resistance of fly ash based geopolymer concrete. Constr. Build. Mater. 2017, 146, 136–143.

61. Othman, R.; Jaya, R.P.; Muthusamy, K.; Sulaiman, M.; Duraisamy, Y.; Abdullah, M.M.A.B.; Sandu, A.V. Relation between density and compressive strength of foamed concrete. Materials 2021, 14, 2967.

62. Othman, R.; Muthusamy, K.; Sulaiman, M.A.; Duraisamy, Y.; Jaya, R.P.; Wei, C.B.; Śliwa, A. Compressive strength and durability of foamed concrete incorporating Processed Spent Bleaching Earth. Arch. Civ. Eng. 2022, LXVIII, 627–643.

63. Gencel, O.; Bilir, T.; Bademler, Z.; Ozbakkaloglu, T. A Detailed Review on Foam Concrete Composites: Ingredients, Properties, and Microstructure. Appl. Sci. 2022, 12, 5752.