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*Review Article*

# An Overview of the Impact of Fly Ash and Polypropylene Fiber on the Mechanical Properties of Foam Concrete

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**Abstract**

Foam concrete is a significant engineering research topic considering its lightweight, high homogeneity, low cost, and low thermal conductivity (<0.5 W/mK). These reasons enhanced good property become an important achievement and modify the use of foamed concrete. This paper includes a review of the effect of added material to the foamed concrete (coarse fly ash, fine fly ash, and fiber reinforcement) on the elastic modulus of concrete. The results show that the addition of fly ash as a fine aggregate decreases the elastic modulus value (E-value) by 20% compared to specimens without fly ash, while reducing dry shrinkage by 35% when 30% of cement is replaced with fine fly ash of density equal to 1400 Kg/m3, also reducing the heat of hydration by adding 0.15 % polypropylene fiber, increasing the E-value by 14.41 % for a density of 1600 Kg/m3 and increasing the E-value by 65.6% for a density of 1800 Kg/m3. The E-value of foamed concrete is equal to about 0.25 of the E-value of normal weight concrete, and the value of static modulus of elasticity typically varies between 1000 and 8000 MPa in foamed concrete. Also, proposed models given in the literature to predict modulus of elasticity in different situations with different additional materials are given in this paper.



## 1. Introduction

Since its inception, concrete has become one of the most popular building materials in the world. It has a wide range of construction applications, such as residential houses, high-rise buildings, pavement, and even water storage tanks [1]. Foresight groups around the world have identified the future need for construction materials that are light, durable, simple to use, economical, and yet more environmentally sustainable. An alternative material that has the potential to fulfill all these requirements is foamed concrete [2]. The history of foam concrete returns to the early 1920s when they produced autoclaved aerated concrete, which was used mainly as insulation. A detailed study concerning the composition, physical properties, and production of foam concrete was first carried out in the 1950s and 1960s. The foamed concrete is a sustainable building material that uses minimal natural materials, as it does not contain any coarse aggregate compared to conventional concrete [1]. Typically, the mixture composition in foamed concrete is made up of cementitious binder, sand, water, and entrained air, so that it contains no coarse aggregate. In composition, it is thus perhaps more closely related to paste or mortar. Some researchers refer to it as a highly air-entrained cement sand slurry [3]. The British Cement Association has defined foamed concrete as "a lightweight material produced by incorporating preformed foam into a base mix of cement paste or mortar, using a standard or proprietary mixing plant." The entrapped air bubbles reduce the density of the base mix and have a strong plasticizing effect on it [4]. Foamed concrete is defined as a light cellular concrete that can be classified as lightweight concrete (density of 400 to 1850 kg/$m^3$) with random air voids created from the mixture of foam agents in mortar [3]. Foam concrete is produced either by the preforming method or the mixed foaming method. The preforming method comprises producing a base mix and stable preformed aqueous foam separately and then thoroughly blending foam into the base mix. In mixed foaming, the surface-active agent is mixed along with base mix ingredients, and during the process of mixing, foam is produced, resulting in cellular structure in concrete. The foam must be firm and stable so that it resists the pressure of the mortar until the cement takes its initial set and a strong skeleton of concrete is built up around the void filled with air. The preformed foam can be either wet or dry foam [5]. With the innovation of foamed concrete, some components of the building can be replaced by lightweight foamed concrete to gain advantages such as sustainability, environmental impact reduction, and decreased cost of construction as well as maintenance cost [1, 6]. In practice, foamed concrete has been commonly used in construction applications due to its distinctive properties, including density reduction, low thermal conductivity, high flowability, and self-compacting concrete. Given the ease of producers and its relative cost-effectiveness, foamed concrete has been found in applications in many civil and structural engineering areas. For example, low-density foamed concrete has been used for cavity filling and insulation, while high densities were used in structural applications. Other applications of foamed concrete include (1) the production of lightweight blocks and pre-cast panels, (2) fire insulation, (3) thermal and acoustic insulation, (4) road sub-base, (5) trench reinstatement, (6) soil stabilization, and (7) shock-absorbing barriers for airports and regular traffic. Also, due to flow-ability features, it is a superlative material for voids such as old sewers, storage tanks, basements, ducts, and voids under roadways that occurred by the cliff of heavy rains [7]. The rising interest in lightweight and sustainable construction materials has led to the exploration of foam concrete, which benefits from the incorporation of additives such as fly ash and polypropylene fiber. However, the variability in mechanical properties—such as compressive strength, tensile strength, and durability—remains a significant concern due to inconsistent results in existing studies. Recent studies indicate that the inclusion of fly ash not only enhances the workability and strength of foam concrete but also contributes to sustainability by reducing the carbon footprint associated with cement production [8]. Additionally, the integration of polypropylene fiber has been shown to improve the tensile and flexural strength, thereby increasing the overall durability and resistance to cracking under various loading conditions [9].

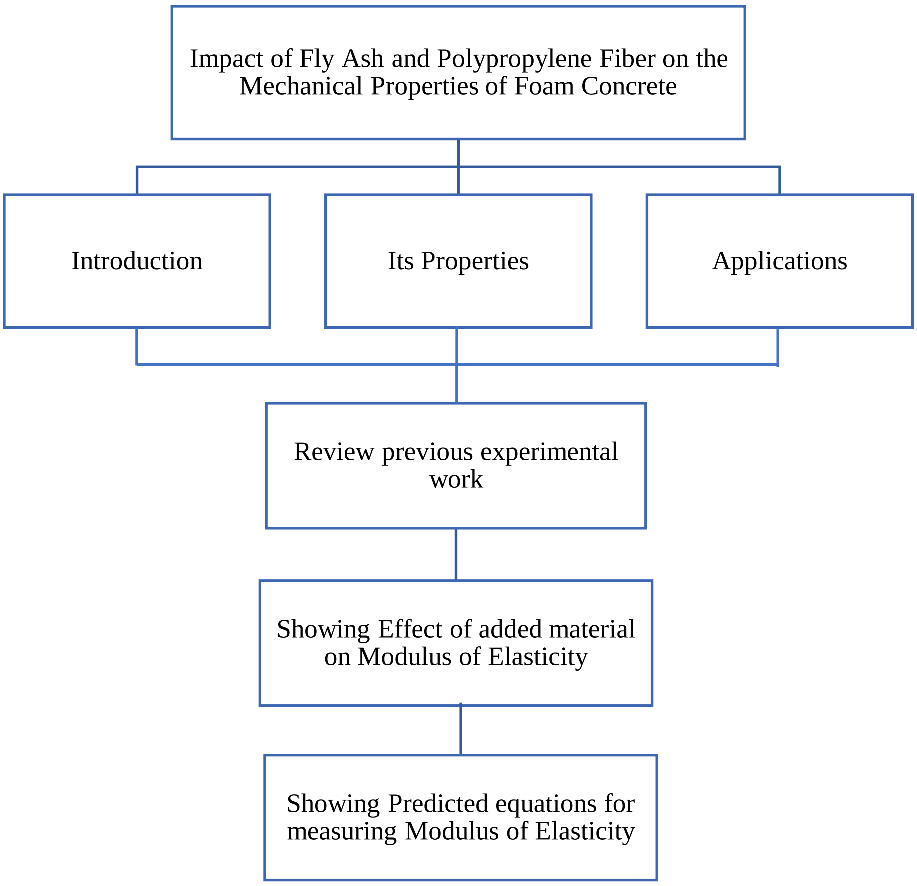


**Figure 1.** Methodology flow chart

The article systematically analyzes these advancements, emphasizing the importance of optimizing the proportions of both materials to achieve superior mechanical properties while promoting environmentally friendly construction practices. In order to investigate how the addition of different materials affects the mechanical properties of foam concrete, this paper focuses on reviewing previous experimental investigations. The objective of the review article is to systematically evaluate and summarize the effects of incorporating fly ash and polypropylene fiber on the mechanical properties of foam concrete. It highlights the significance of adding polypropylene fibers and fly ash to the foam concrete mixture. The review emphasizes the impact on important characteristics, particularly the modulus of elasticity (E), which is essential to comprehending foam concrete's structural performance. The article attempts to give a thorough review of how these additives can improve the mechanical properties of the material by examining the results from numerous research studies. A flowchart in Figure 1 shows the progress of the study.

## 2. Properties of Foamed Concrete

### 2.1. Compressive Strength

Compressive strength is one of the mechanical properties of the material and is obtained as a result of a test on prepared samples and is affected by many factors such as mix proportion, condition of preparation concrete, placement of concrete, curing, In foam concrete, the compressive strength is mostly affected by the foam content rather than its reliance upon the water-cement ratio [10]; the compressive strength of a foamed concrete is highly influenced by the type of the foaming agent, such as the protein-based foam agent, more than the synthetic foam agent [11]. However, Wee et al. [12] reported through both experimental and numerical studies that the inclusion of air bubbles in foam concrete is more influential on compressive strength than on modulus of elasticity.

Additionally, a study by [13] and [14] found that incorporating supplementary cementitious materials (SCMs) can enhance both the mechanical properties and sustainability of foam concrete, further complicating the relationship between material composition and compressive strength. Similarly, Li et al. found that polypropylene fibers help to reduce the production of microcracks during the curing process, resulting in a more resilient material [14]. Furthermore, Jhatial et al. found that fiber reinforcement improves energy absorption and ductility, allowing foam concrete to withstand dynamic loads more effectively. These findings indicate that using polypropylene fibers in foam concrete formulations can greatly improve its mechanical qualities [15].

### 2.2. Flexural and Tensile Strength

The flexural strength of foam concrete is lower than that of equivalent normal weight and lightweight aggregate concrete. It was reported that for foam concrete, the ratio of flexural strength to compressive strength varies between 0.2 and 0.4, which is higher than normal concrete (0.08 and 0.11) [16]. The addition of additional substances, such as fly ash and polypropylene fibers, has been proven to increase the flexural strength of foam concrete. Fly ash, a pozzolanic ingredient, improves not just the mix's workability but also its microstructural characteristics, resulting in greater bonding within the matrix. According to research, adding fly ash may improve flexural strength by improving the hydration process and creating a denser microstructure [17]. Similarly, the addition of polypropylene fibers has a considerable effect on the flexural properties of foam concrete. Raksiri et al. discovered that polypropylene fibers improve ductility while also contributing to increased energy absorption during flexural stress [18]. These fibers improve the overall strength of the foam concrete structure by reducing crack development. The combination of fly ash and polypropylene fibers produces a composite material with higher mechanical properties, making foam concrete more suitable for applications that require increased flexural strength.

### 2.3. Modulus of Elasticity

The static modulus of elasticity of foam concrete is reported to be significantly lower than that of normal weight and lightweight concrete, with values typically varying from 1.0 to 8.0 kN/mm$^2$ [5]. Understanding the factors that influence the modulus of elasticity, such as the mix design, type and proportion of additives like fly ash and polypropylene fibres, and the curing conditions, is crucial for optimizing foam concrete's performance for various applications. The research presented in the paper underlines the need to explore how these additives may potentially improve the mechanical properties, including the modulus of elasticity.

## 3. Effect of Added Material on Modulus of Elasticity

Much research has been done on foam concrete, and many researchers have trained to modify foam concrete composition to obtain eco-friendly foam concrete with performable properties. Any materials when added to the mix will affect these concrete properties at different rates. Jones and McCarthy [11] describe a laboratory study of the development of foamed concrete utilizing two types of fly ash: fine fly ash (BS EN 450) was used to partially replace Portland cement, and coarse fly ash (BS 3892-2) to replace sand fine aggregate. Also, polypropylene fiber has been used for modifying tensile and plasticity properties. The main objective was to determine the lowest foamed concrete density that could be produced to have a compressive strength of at least 25 MPa. After de-molding at 24 h, the specimens were sealed, cured, and stored at 20 oC until testing. BS 1881-126., 1983, used to measure static modulus of elasticity. The majority of the foamed concrete E-values were significantly lower than those calculated for normal weight concrete and light-weight concrete specimens, with values increasing almost linearly with density. From the test result obtained, FA coarse specimens exhibited lower E-values than the sand fine aggregate concretes, and the result comparison showed that normal-weight concrete exhibited values up to four times higher than equivalent foamed concrete. This has considerable implications for the use of foamed concrete in flexural applications, as deflection could be expected to be much higher given a particular load and section geometry. Also, E-value increased with the addition of fibers, with the most marked increases noted at 0.5% rate and 1400 $Kg/m^3$.

Ramamurthy et al. [5] and Pauw [19] investigated foam concrete by use of the proportion of cement in the range (335–446) $Kg/m^3$, S/C ( sand to cement ratio ) in the range ( 0.79 – 2.8 ) also w/c ( water to cement ratio ) in the range ( 0.33 – 0.57 ), and density range (800–1800) $kg/m^3$, and obtained compressive strength from a 28-day cured sample in the range ( 1.8 – 17.6 ) MPa also states that the E-value of foamed concrete typically varies between 1.0 and 8.0 $kN/mm^2$, which is usually 0.25 of the E-value in normal weight concrete. They also state that the value of E increases 2 to 4 times by using polypropylene in the mix. Brady et al. showed that the modulus of elasticity (E) for foamed concrete ranges from 1 to 12 $kN/mm^2$ for dry densities of 500 to 1600 $kg/m^3$, respectively [20]. By comparison, the E-value for structural concrete having a compressive strength of 40 MPa is about 28 $kN/mm^2$. This large difference can be attributed to the lack of coarse aggregate in the former. For the same strength, the former have much higher E-values; again, this is probably due to the interlocking of the fine aggregate. The addition of 0.5 percent of polypropylene fibers to foamed concrete beams increased their stiffness by a factor of between 1.7 and 4.6. These enhanced values are still much lower than for normal-weight concrete. Thus, much greater deflection is observed in foamed concrete beams than ones formed from normal-weight concrete; furthermore, the former exhibit a slightly more brittle failure but one that was not sudden or explosive. Jhatial et al. [21] prepared foamed concrete with two different densities, 1600 $kg/m^3$ and 1800 $kg/m^3$. Four different percentages of polypropylene (PF) (fiber size 19 mm and 0.9 specific gravity): 0, 0.05, 0.1, and 0.15 % of PF were added in both densities of foamed concrete, while the maximum mix proportion of foamed concrete was selected as a 1:2 cement-sand ratio and the water-to-cement ratio was taken as 0.55. Compressive strength tests and modulus of elasticity were conducted to determine the effect of the PF in foamed concrete. To determine modulus of elasticity, samples were cured for 28 days, and based upon the results, the maximum percentage of PF was determined to be 0.15 % at which higher compressive strength and modulus of elasticity for both densities were obtained as in Table 1.

**Table 1.** E-value based of polypropylenes ratio at different densities [21]

| **Polypropylenes fibres %** | **Modulus of elasticity (MPa)** | |
|---|---|---|
| | **1600 Kg/m$^3$** | **1800 Kg/m$^3$** |
| 0 | 7945 | 10643 |
| 5 | 8051 | 10819 |
| 10 | 8377 | 16131 |
| 15 | 9090 | 17567 |

According to Kozłowski and Kadela [22], foamed concrete has become a promising material for concrete structural purposes. A serious test was carried out to examine the mechanical properties of foamed concrete mixes without fly ash and with fly ash content. The results observed that there were exponential relationships for concrete mixes without fly ash (FC) and with fly ash (FCA). The specimens without fly ash seem to have a higher modulus of elasticity than the mixtures containing fly ash. In addition, the influence of 25 cycles of freezing and thawing on the compressive strength was investigated. An increase in the density of foamed concrete results in a decrease in flexural strength; also, compressive strength from a mix containing fly ash is approximately lower by 20 % than the compression from a mix not containing fly ash. Also, specimens subjected to 25 freezing and thawing cycles show approximately 15 % lower compressive strength compared to the untreated specimens. The modulus of elasticity of specimens without fly ash seems to be higher than the mixtures containing fly ash. Hilal et al. [23] describe an experimental study of preformed foamed concrete with a density of 1300–1900 kg/m$^3$ by adding two types of additives, silica fume and fly ash, to partially replace Portland cement and fine sand. Foamed concrete mixes with high flow ability and strength (FCa) were also manufactured in this study. The foam concrete (FC) mix had 28-day compressive strengths from 6 to 23 MPa, whereas for the same density range, the FCa mixes gave 19-47 MPa. The static modulus of elasticity (E-value) of the mixtures were determined using a 150 * 300 mm cylinder specimen. Two specimens were tested for each mix at an age of 28 days in accordance with BS 1881-121:1983, and from stress-strain compression curves the value of ES was determined. Note that for a given compressive strength, the FCa mix exhibits a lower E-value than the FC mix, while the E-value for NWC is higher than for both FC and FCa. Othuman Mydin et al. [24] report the main findings from a comprehensive study undertaken to evaluate the thermal and mechanical properties of lightweight foamed concrete (LFC) exposed to high temperatures. LFC of densities of 650 and 1000 kg/m$^3$ was comprehensively tested. To quantify thermal conductivity, LFC is treated as porous material, and the effects of radiant heat transfer within the porous are included. The elevated mechanical property models consist of two parts: the prediction of compressive modulus of elasticity and peak stress as functions of porosity and the prediction of strength and stiffness retention factors as a function of temperature. The LFC is based on Portland cement CEM1, fine sand, water, and stable foam. The Portland cement was used because the main purpose of this research was to establish a method to obtain reliable LFC thermal and mechanical properties at elevated temperatures. The cement-sand ratio was 2:1 and the water-cement ratio (w/c) were 0.5; the foamed agent used was Noraite PA-1; and the densities of casted samples were 650 and 1000 kg/m$^3$. The dehydration process starts as early as 90 °C. In the range of 90–170 °C, the evaporation of free water and part of the chemical bond water escape. Some chemical bond water is also lost through the decomposition of the calcium silicate hydrates (C-S-H) gel that takes place between 120 °C and 140 °C and the decomposition of ettringite around 120 °C. In the temperature range of 200-300 °C, some of the chemical bond water is released from further decomposition of the C-S-H gel and sulfate aluminate phases of the cement paste. Further dehydration occurs at around 450 °C, which corresponds to the decomposition of calcium hydroxide ($Ca(OH)_2$) into calcium oxide (CaO) and water H2O. (Ca (OH)2→ CaO+H2O), and is completed at 530 °C. The Euro code does not have a direct model for the modulus of elasticity as a function of temperature.

Richard and Ramli [25] studied the base mix parameters to produce sustainable foamed concrete by substituting cement, which is a source of carbon dioxide, a greenhouse emission element, with a cementitious material, fly ash, within a range of 10% up to 50%, and a water cement ratio of 0.3. Notraite PA-1 was used as a foaming agent, and the pre-foamed method was adopted for the production of the foamed concrete, with a target density of 1600 kg/m$^3$. The cement in this paper was ordinary Portland cement; the class F fly ash was used; the fine aggregate size was 300 µm and of a specific gravity of 2.52; portable water was also used; but no chemical additive was used in this experiment. Each test result is represented by three 100 mm cube samples, and all were tested to determine their density and compressive strength at various 7, 14, and 28 days after water, moisture, and air curing. The modulus of elasticity of the samples was determined according to BS 1881, Part 121, and it was observed to be as a matter of the compressive strength of foamed concrete. In this study, it was calculated at the ages of 7, 14, and 28 days. This is found to be higher, and it may be due to the interlocking of fine aggregates used in the base mix.

However, generally, it is observed that the modules of elasticity of foamed concrete are far lower compared to that of normal-weight concrete, and this is a result of the absence of coarse aggregate in the mix.

**Table 2.** Predicted models for finding Modulus of elasticity

| References | Enhanced model | Remark |
|---|---|---|
| Brady et al., [20] | $E = 0.94\, fc' - 2.8$ | For foam concrete with sand |
| Brady et al., [20] | $E = 0.24\, fc' + 2.5$ | For foam concrete containing fly |
| Jones and McCarthy [2] | $E = 0.42 * (fc')^{1.18}$ | Sand fine aggregate<br>E: is static modulus of elasticity by kN/mm$^2$<br>fc': 100 mm cube strength (sealed cured) (N/mm$^2$) |
| Jones and McCarthy [11] | $E = 0.99 * (fc')^{0.67}$ | Fly ash coarse sand fine aggregate<br>E: is static modulus of elasticity by kN/mm$^2$<br>fc': 100 mm cube strength (sealed cured) (N/mm$^2$) |
| Ramamurthy et al., [5] and Pauw., [19] | $E = 33 * W^{1.5} * \sqrt{fc'}$ | Pauw's Equation (PSI) can be used for light and normal weight concrete |
| Ramamurthy et al., [5] and Saint-Jalmes et al., [26] | $E = 5.31 * W - 853$ | Density from 200 to 800 Kg/m$^3$<br>E: is static modulus of elasticity by kN/mm$^2$<br>fc': 100 mm cube strength (N/mm$^2$)<br>W: Density of concrete (Kg/m$^3$) |
| Othuman Mydin et al., [24] | $E_{CT} = E_C$ | $for\ T \leq 60^O C$ |
| Othuman Mydin et al., [24] | $E_{CT} = \frac{800 - T}{740} E_C$ | $for\ 60^O C \leq T \leq 800^O C$ |
| Amran et al., [7] and Byun et al., [27] | $E = 6326 * (\gamma_{con})^{1.5} * (fc')^{0.5}$ | Poisson ration = 0.2 and use polymer foam agent<br>E: is static modulus of elasticity by kN/mm$^2$<br>fc': 100 mm cube strength (N/mm$^2$)<br>γ: Density of concrete (Kg/m$^3$) |
| Amran et al., [7] and Rowe et al., [4] | $E = 9.1 * (fc')^{0.33}$ | E: is static modulus of elasticity by kN/mm$^2$<br>fc': 100 mm cube strength (N/mm$^2$)<br>ρ: plastic density of concrete (Kg/m$^3$) |
| Amran et al., [7] and Rowe et al., [4] | $E = 1.7 * 10^{-6} * (\rho)^2 * (fc')^{0.5}$ | E: is static modulus of elasticity by kN/mm$^2$<br>fc': 100 mm cube strength (N/mm$^2$)<br>ρ: plastic density of concrete (Kg/m$^3$) |
| Kadela and Kozłowski., [28] | $E = fc' + 0.8\, \rho^{2.9606}$ | Obtained from numerical analysis by software |
| Jhatial et al., [21] | - | Showed how E-value increase with PE in foam concrete by data |
| Kozłowski and Kadela., [22] | $E = 0.5fc' + 0.25\, \rho^2 + 0.006\, \rho - 1.6$ | For foam concrete not containing fly ash R2=0.99 |
| Kozłowski and Kadela., [22] | $E = fc' + 0.5\, X^2 + 0.0103\, X - 2.72$ | For foam concrete containing fly ash R2=0.99 |
| Hilal et al., [23] | $E = 0.99\, (f_{cu})^{0.67}$ | For foam concrete contain fly ash |
| Hilal et al., [23] | $E = 0.42\, (f_{cu})^{1.18}$ | For foam concrete with sand |

## 4. Predicted Equation of Modulus of Elasticity

The predicted equation to measure the modulus of elasticity of foam concrete from different sources is as described in Table.2

## 5. Conclusion

This study investigates the influence of various material additions on the mechanical properties of foamed concrete, with a particular focus on its elastic modulus (E-value), a key indicator of stiffness. The findings reveal that incorporating fly ash as a fine aggregate reduces the E-value by 20% compared to specimens without fly ash, due to its pozzolanic nature, which improves workability and decreases the concrete's density. Furthermore, replacing 30% of ordinary Portland Cement (OPC) with fine fly ash in a mixture with a density of 1400 kg/m³ reduces dry shrinkage by 35%, attributed to enhanced hydration and a denser microstructure. Adding 0.15% polypropylene fibers increases the E-value by 14.41% for concrete with a density of 1600 kg/m³ and by 65.06% for 1800 kg/m³, due to the reinforcing properties of the fibers that bolster the load-bearing capacity. Overall, the E-value of foamed concrete is approximately 0.25 that of normal-weight concrete, highlighting substantial differences in mechanical properties. Additionally, the static modulus of elasticity in foamed concrete ranges from 1.0 to 8.0 kN/mm², reflecting the variability in mechanical performance based on composition and density.

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## References

[1] T. Irawan and Y. Idris, "Mechanical properties of foamed concrete with additional pineapple fiber and polypropylene fiber," in *Journal of Physics: Conference Series*, 2019, vol. 1198, no. 8, p. 082018: IOP Publishing.

[2] M. Jones and A. McCarthy, "Behaviour and assessment of foamed concrete for construction applications," in *Use of foamed concrete in construction: Proceedings of the international conference held at the University of Dundee, Scotland, UK on 5 July 2005*, 2005, pp. 61-88: Thomas Telford Publishing.

[3] V. Bindiganavile and M. Hoseini, "University of Alberta, Edmonton, AB, Canada," *Developments in the Formulation and Reinforcement of Concrete*, p. 365, 2019.

[4] R. Rowe, G. Somerville, and A. Beeby, *Handbook to british standard BS8110: 1985: structural use of concrete*. Palladian, 1987.

[5] K. Ramamurthy, E. K. Nambiar, and G. I. S. Ranjani, "A classification of studies on properties of foam concrete," *Cement and concrete composites*, vol. 31, no. 6, pp. 388-396, 2009.

[6] S. A. Ahmad, A. J. Nimat, and H. F. Mahmood, "Effect of Different Types and Ratio of Fibers on the Tensile Strength of Reinforced Foam Concrete: A Review," *Emerging Technologies and Engineering Journal,* vol. 1, no. 2, pp. 72-83, 2024.

[7] Y. M. Amran, N. Farzadnia, and A. A. Ali, "Properties and applications of foamed concrete; a review," *Construction and Building Materials,* vol. 101, pp. 990-1005, 2015.

[8] Y.-g. Chen, L.-l. Guan, S.-y. Zhu, and W.-j. Chen, "Foamed concrete containing fly ash: Properties and application to backfilling," *Construction and building materials,* vol. 273, p. 121685, 2021.

[9] Y. Xu, L. Yao, and X. Yu, "Effect of polypropylene fibers on mechanical and wetting properties of overall superhydrophobic foamed concrete," *Construction and Building Materials,* vol. 448, p. 138207, 2024.

[10] M. Nehdi, A. Khan, and K. Lo, "Development of deformable protective system for underground infrastructure using cellular grouts," *Materials Journal,* vol. 99, no. 5, pp. 490-498, 2002.

[11] M. Jones and A. McCarthy, "Preliminary views on the potential of foamed concrete as a structural material," *Magazine of concrete research,* vol. 57, no. 1, pp. 21-31, 2005.

[12] T.-H. Wee, D. S. Babu, T. Tamilselvan, and H.-S. Lim, "Air-void system of foamed concrete and its effect on mechanical properties," *ACI materials journal,* vol. 103, no. 1, p. 45, 2006.

[13] L. Zhao, Q. Huang, Q. Xue, S. Yao, and X. Li, "Preparation and characterization of a fly ash and cement-based foam composite," *Materials Express,* vol. 10, no. 10, pp. 1758-1763, 2020.

[14] S. Li, H. Li, C. Yan, Y. Ding, X. Zhang, and J. Zhao, "Investigating the Mechanical and Durability Characteristics of Fly Ash Foam Concrete," *Materials*, vol. 15, no. 17, p. 6077, 2022.

[15] A. A. Jhatial, W. I. Goh, A. K. Mastoi, A. F. Traore, and M. Oad, "Environmental assessment and mechanical properties of Polypropylene fibres reinforced ternary binder foamed concrete," *Environmental Science and Pollution Research,* vol. 29, no. 2, pp. 2985-3007, 2022.

[16] A. Raj, D. Sathyan, and K. Mini, "Physical and functional characteristics of foam concrete: A review," *Construction and Building Materials*, vol. 221, pp. 787-799, 2019.

[17] L. Gupta and R. Kumar, "Experimental investigation of reclaimed asphalt foamed bituminous mix: A cold mix technique," *World Journal of Engineering,* vol. 20, no. 4, pp. 655-668, 2023.

[18] R. Sukkarak, P. Jongpradist, P. Jamsawang, P. Sukontasukkul, and P. Chindaprasirt, "Effect of polypropylene fiber on the flexural strength properties of lightweight foam mixed soil," *Advances in Materials Science and Engineering,* vol. 2019, no. 1, p. 1607325, 2019.

[19] A. Pauw, *Static modulus of elasticity of concrete as affected by density*. University of Missouri, 1960.

[20] K. Brady, G. Watts, and M. R. Jones, "Specification for foamed concrete," 2001.

[21] A. A. Jhatial *et al.*, "The mechanical properties of foamed concrete with polypropylene fibres," *International Journal of Engineering & Technology,* vol. 7, no. 3.7, pp. 411-413, 2018.

[22] M. Kozłowski and M. Kadela, "Mechanical characterization of lightweight foamed concrete," *Advances in Materials Science and Engineering,* vol. 2018, no. 1, p. 6801258, 2018.

[23] A. A. Hilal, N. Thom, and A. Dawson, "The use of additives to enhance properties of pre-formed foamed concrete," *International Journal of Engineering and Technology,* vol. 7, no. 4, 2015.

[24] M. A. Othuman Mydin and Y. C. Wang, "Thermal and mechanical properties of lightweight foamed concrete at elevated temperatures," *Magazine of Concrete Research,* vol. 64, no. 3, pp. 213-224, 2012.

[25] A. O. Richard and M. Ramli, "Experimental production of sustainable lightweight foamed concrete," *British Journal of Applied Science & Technology,* vol. 3, no. 4, pp. 994-1005, 2013.

[26] A. Saint-Jalmes, M.-L. Peugeot, H. Ferraz, and D. Langevin, "Differences between protein and surfactant foams: Microscopic properties, stability and coarsening," *Colloids and Surfaces A: Physicochemical and Engineering Aspects,* vol. 263, no. 1-3, pp. 219-225, 2005.

[27] K. Byun, H. Song, S. Park, and Y. Song, "Development of structural lightweight foamed concrete using polymer foam agent," *ICPIC-98*, vol. 9, 1998.

[28] M. Kadela and M. Kozłowski, "Foamed concrete layer as sub-structure of industrial concrete floor," *Procedia Engineering*, vol. 161, pp. 468-476, 2016.