Journal of Advanced Research in Fluid Mechanics and Thermal Sciences 109, Issue 1 (2023) 13-26

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879

Thermal Performance and Electrical Sensitivity of Foamed Concrete Incorporating Ground Granulated Blast-Furnace Slag (GGBS)

Afiya Abdul Sattar[1], Md Azree Othuman Mydin[1,*], Roshartini Omar[2]

[1] School of Housing, Building and Planning, Universiti Sains Malaysia, 11800, Penang, Malaysia
[2] Department of Construction Management, Faculty of Technology Management and Business (FPTP), Universiti Tun Hussein Onn Malaysia (UTHM), Parit Raja, Batu Pahat, 86400 Johor, Malaysia

ARTICLE INFO

Article history:
Received 9 June 2023
Received in revised form 7 August 2023
Accepted 18 August 2023
Available online 5 September 2023

ABSTRACT

The steady stream of technological advancements in the realm of construction materials has engendered an increased emphasis on the investigation of foamed concrete produced with agricultural waste, with the aim of enhancing the resilience and thermodynamic attributes of foamed concrete. The transport characteristics and aggressive ions via the foamed concrete microstructure partially govern degradation processes in foamed concrete structures that impact durability. Ions are charged, therefore the capacity of foamed concrete to resist ion transfer is heavily dependent on its electrical resistivity and thermal performance. As a result, a link between the electrical resistivity and thermal characteristics of foamed concrete and degradation processes such as increased permeability and corrosion of embedded steel might be envisaged. Therefore, the present study aims to investigate the prospective application of ground-granulated blast-furnace slag (GGBS) in foamed concrete, specifically examining its impact on the electrical sensitivity and thermal conductivity of said material. The objective of this study is to determine the electrical sensitivity and thermal conductivity of foamed concrete when GGBS is incorporated. The density of 800 kg/m^3 was made and evaluated. Various weight fractions of GGBS ranging from 10% to 50% were employed. Five durability properties of foamed concrete were assessed, namely electric sensitivity, porosity, water absorption, thermal diffusivity, and thermal conductivity. The experimental findings demonstrated that the incorporation of 30% of GGBS yielded the most favourable outcomes in terms of durability properties. When the weight fraction of GGBS reached 30%, maximum compaction was achieved in the cement matrix, resulting in exceptional mix regularity. The presence of GGBS at inclusion levels exceeding 30% resulted in the observation of both accumulation and non-uniform dispersion of GGBS particles. These phenomena subsequently caused a decrease in the overall parameters that were evaluate.

Keywords:
Foamed concrete; ground granulated blast furnace slag; thermal conductivity; electrical sensitivity; porosity; water absorption

1. Introduction

The exponential surge in energy utilization pertaining to architectural endeavours, particularly in the domain of heating, ventilation, air conditioning, and cooling (HVAC), poses a formidable obstacle to the worldwide energy reservoir [1,2]. The energy requirements linked to these indispensable building necessities encompass approximately one-third of global energy usage, thereby leading to

---

[*] *Corresponding author.*
E-mail address: azree@usm.my

https://doi.org/10.37934/arfmts.109.1.1326

roughly 40% of overall carbon dioxide emissions as a consequence of the expeditious exploitation of fossil fuels [3,4]. The issue of climate change resulting from anthropogenic greenhouse gas emissions has garnered considerable attention from researchers [5]. They have been actively exploring various strategies to enhance energy efficiency in buildings [6-9]. Concrete is a highly advantageous and versatile material when it is cast into the formwork [10]. The prioritization of concrete's rigidity and strength has been established [11]. This phenomenon can be attributed to the structural behavior of concrete, which enables it to effectively bear the combined weight of both dead and live loads [12]. Given the extensive body of research conducted on concrete over the years, there is a burgeoning interest among researchers to conduct studies aimed at enhancing the efficacy of concrete for application within the construction industry [13-15]. Foamed concrete has emerged as an innovative solution in the construction industry, aimed at achieving lighter and more sustainable buildings [16-19].

In recent years, the demand for and utilization of foamed concrete as a building material has attained a privileged status within the construction industry. This is primarily attributed to its commendable features, including but not limited to its reduced weight, exceptional thermal insulation capabilities, and remarkable durability [20-23]. Foamed concrete exhibits a reduced weight in comparison to conventional weight concrete, owing to the presence of artificially introduced air bubbles that are effectively entrapped within its cement mortar, facilitated by the utilization of a suitable foaming agent [24,25]. The exclusion of coarse aggregate in the production of foamed concrete, coupled with the potential substitution of renewable materials like pulverized fuel ash, silica fume, and ground-granulated blast furnace, allows for the partial or complete replacement of cement in the aforementioned process [26-30]. Furthermore, it is worth noting that foamed concrete exhibits considerable promise as a viable option for utilization as a structural material, boasting a commendable strength threshold of 27N/mm^2 [31-35]. Typically, the compressive strength of foamed concrete, spanning a range of densities from 550 kg/m^3 to 1050 kg/m^3, is observed to vary between 1 MPa and 6 MPa [36].

The relationship between density and porosity assumes a pivotal role in exerting control over the strength of foamed concrete [37]. The use of pozzolan elements as replacements for cement or sand in the composition of concrete has been recognized as a common practice throughout the history of human civilization. These materials are used either in their natural condition or by artificial means. In addition to the prevailing economic and environmental considerations, empirical evidence has substantiated the efficacy of incorporating foamed concrete in bolstering its inherent strength, which is otherwise deemed relatively feeble. The examination of thermal properties and electric sensitivity has long been a subject of paramount importance. The impact of various agricultural wastes on the mechanical characteristics of foamed concrete, however, remains little understood [38].

The durability of foamed concrete can be characterized by its capacity to withstand the effects of weathering, chemical assault, abrasion, or any other form of deterioration while maintaining its initial structure, excellence, and functionality when subjected to adverse environmental conditions. To a considerable degree, it is widely acknowledged that the durability of foamed concrete is primarily determined by its capacity to withstand the infiltration of corrosive substances. The aforementioned medium has the potential to exist in either a liquid or gaseous form and can be conveyed through a variety of mechanisms including permeation, diffusion, absorption, capillary suction, and various combinations thereof [39]. Therefore, in the context of foamed concrete utilization, it is plausible to consider the prevalence of a synergistic interplay among multiple mediums, leading to the occurrence of hybrid modes of transportation processes. Furthermore, it is worth noting that there exist intricate interconnections among the transport parameters of foamed concrete and a multitude of durability characteristics [40,41]. Thus, the transportation of ions across the intricate microstructure of foamed concrete assumes a pivotal role in the regulation of concrete's long-lasting quality [42]. The electrical resistivity and thermal properties of foamed concrete play a crucial role in determining its capacity to endure the transmission of charged ions when they are in an electric state [43]. Thermal conductivity and electrical resistivity are fundamental material properties that possess versatile applications, including the ability to discern the initial stage attributes of newly formed foamed concrete [44]. Upon the solidification and consolidation of the fresh foamed concrete, the process of depercolation, results in an elevation of its thermal conductivity, electrical resistivity, and thermal diffusivity [45]. The flow of heat and electrical current through the foamed concrete pore solution, facilitated by the movement of charged ions, serves as a reliable indicator of the underlying foamed concrete pore structures [46]. The development of pore structure during the early stages of concrete formation plays a crucial role in determining its long-term durability [47]. Furthermore, it should be noted that cementitious materials like FC exhibit a relatively low tensile strength during the early stages of their development, rendering them susceptible to the occurrence of cracks [48.49]. The initial cracking phenomenon also functions as a means for harmful substances to enter the matrix. The phenomenon of cracking in foamed concrete can also be assessed through thermal tests and resistivity measurements, which in turn aids in the prediction of the concrete's long-term durability [50-52]. Furthermore, the utilization of thermal conductivity and electrical resistivity serves as a valuable indicator for assessing both the moisture content and the interconnectedness of the micropores within the concrete material [53]. Hence this research explored the potential utilization of GGBS as cement replacement in the production of foamed concrete.

2. Methodology

2.1 Materials

The cement utilized in this investigation was Ordinary Portland Cement, adhering to the BS EN 12 specification, and was procured from YTL Sdn. Bhd. The entirety of the cement consumed was found to be in satisfactory condition and had been appropriately stored within a sheltered location. The fine sand was obtained from a local supplier and was of natural origin. The fine sand under consideration exhibited a maximum width of 2 mm and was subjected to a 600-micron sieve, resulting in a passage range of 60% to 90%. The appropriateness of the sand had to adhere to the specifications outlined in the BS EN 822. Subsequently, the foaming agent employed in the study was Noraite PA-1, which is a protein-based foaming agent. The foam was generated using a portable foaming generator machine known as the Portafoam TM-1 machine. A water-cement ratio of 0.45 was selected for this study due to its ability to attain a satisfactory level of workability. The GGBS employed in this study was provided by DRN Technologies Sdn. Bhd. shown in Figure 1. Table 1 presents a comprehensive overview of the chemical composition of the GGBS, while Table 2 provides an exposition of its physical properties.

Fig. 1. GGBS employed in this study

Table 1
GGBS chemical compositions

Components	GGBS
SiO_2	32.89
Al_2O_3	12.88
Fe_2O_3	2.25
CaO	40.81
MgO	8.47
SO_3	1.93
Na_2O	0.32
K_2O	0.45

Table 2
GGBS physical properties

Components	GGBS
Specific gravity	2.95
Specific surface area (gm/cm^2)	610
Density (kg/m^3)	1185
Fineness modulus	2.39
Moisture contents (%)	17.8

2.2 Mix Design

A total of six foamed concrete mixtures were formulated. A foamed concrete with a medium density of 800 kg/m^3 was manufactured. The experimental conditions encompassed the manipulation of the proportion of cement substitutions with Ground Granulated Blast Furnace Slag (GGBS) at different increments, specifically 0% (serving as the control), 10%, 20%, 30%, 40%, and 50%. In each case, a sand-cement ratio of 1:1.5 was utilized, while the water-cement ratio was maintained at a constant value of 0.45. The mix design of foamed concrete in this study is outlined in Table 3.

Table 3
Foamed concrete mix design containing varying proportions of GGBS

Mix	GGBS (%)	GGBS (kg/m^3)	Sand (kg/m^3)	Cement (kg/m^3)	Water (kg/m^3)	Foam (kg/m^3)
GGBS-0	0	0.0	454	303	136	37
GGBS-10	10	30.3	454	272	136	37
GGBS-20	20	60.5	454	242	136	37
GGBS-30	30	90.8	454	212	136	37
GGBS-40	40	121.0	454	182	136	37
GGBS-50	50	151.3	454	151	136	37

2.3 Experimental Setup

The study evaluated five key durability characteristics of foamed concrete, specifically its electrical sensitivity, porosity, water absorption, thermal diffusivity, and thermal conductivity. This section will outline the experimental methodology employed to achieve the objectives of the investigation. The foamed concrete bulk resistivity was measured by conducting an electrical resistivity test in accordance with the ASTM C1760 standard. The property of electrical resistivity is a material attribute that finds utility in multiple applications, including the identification of early-age properties of newly mixed concrete. The electrical resistivity of fresh concrete increases as the capillary pore space undergoes depercolation, resulting in discontinuity. This occurs when the concrete sets and hardens. The flow of electrical current through the concrete pore solution, facilitated by the movement of charged ions, serves as a reliable indicator of the underlying concrete pore structures. The permeable porosity test was performed in accordance with the procedures specified in the ASTM C1202-17a standard. In accordance with the prescribed protocols outlined in BS 1881-122, the examination pertaining to the water absorption capacity was diligently carried out at regular intervals spanning 7, 14, and 28 days. The thermal diffusivity and conductivity of foamed concrete were determined by employing a guarded hot-plate apparatus in accordance with the esteemed ASTM C177-19. The experimental analysis encompassed the examination of foamed concrete specimens with dimensions measuring 25mm in length, 25mm in width, and 12mm in thickness. The sensor was interposed amidst a pair of composite discs, with an additional duo of discs being superimposed upon the initial arrangement.

3. Results
3.1 Electrical Sensitivity

Figure 2 displays the outcomes of the electrical resistivity analysis conducted on foamed concrete samples with varying quantities of GGBS incorporation. Mix GGBS-30 recorded the best electrical resistivity compared to other mixes. The control mix (GGBS-0) recorded the highest electrical resistivity. It is important to mention that the 28-day electrical resistivity of GGBS-40 is greater than that of GGBS-30. In comparison, the 28-day electrical resistivity of GGBS-50 exhibits a higher value when compared to GGBS-40. The observed phenomenon can be attributed to a higher level of discontinuity in the pore system of GGBS-40 as compared to GGBS-30. It is important to note that the occurrence of defects in both mixtures containing GGBS is higher compared to that of GGBS-50. The inclusion of a pozzolan-like GGBS in a cementitious system facilitates the generation of secondary crystals of C-S-H gel through its reaction with the existing CH [54]. This process contributes to the enhancement of the microstructure [55]. These crystals have the potential to divide larger void spaces into smaller compartments. Consequently, it is probable that a greater quantity of smaller, unconnected pores is formed. The measurement of electrical resistivity serves as an indirect measure of the foamed concrete's capacity to impede the penetration and subsequent movement of harmful chemical ions, specifically chloride and sulphate. The long-term durability of foamed concrete is contingent upon its ability to withstand various environmental and structural factors. It is widely recognized that concrete exhibits a lower electrical conductivity compared to water, specifically referring to the water present within its pores [56]. The presence of a well-connected network of pores filled with pore fluid is clearly associated with higher conductivity in a foamed concrete system, as opposed to a system lacking such interconnections. An additional crucial aspect to contemplate regarding electrical resistivity in foamed concrete pertains to the attributes of its pores, encompassing their frequency or incidence within a three-dimensional realm, alongside the extent of interconnectivity. The mean porosity of a given paste specimen may not invariably serve as a reliable indicator of its inherent permeability. A comprehensive analysis of the spatial arrangement of pores within a paste specimen can yield valuable insights into the existence and attributes of any interconnections present within the sample [57]. It may be more advantageous to possess a greater abundance of diminutive voids within a given specimen as opposed to a lesser quantity of more substantial imperfections. The existence of an intermittent arrangement of diminutive imperfections within a paste specimen, imbued with a pore fluid possessing enhanced conductivity, shall result in an augmentation of electrical resistivity [58]. Conversely, in the context of electrical conductivity, a system distinguished by the presence of substantial defects that are occupied by fluid-filled pores has the potential to augment the movement of electrons and other deleterious chemical ions.

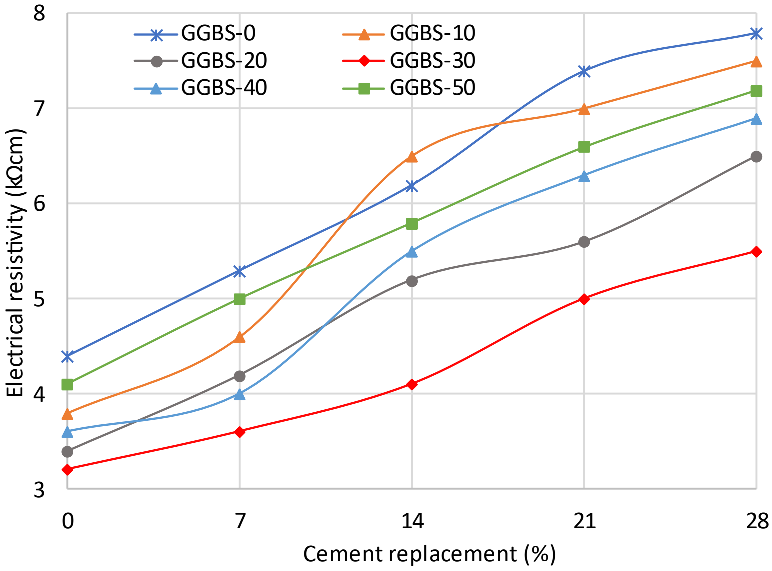

Fig. 2. Electrical resistivity of foamed concrete with various amounts of GGBS addition

3.2 Porosity

The porosity of foamed concrete plays a significant role in determining the characteristics of water transport. It provides insights into the absorption and movement of water through capillary networks within the permeable medium. The results of measurements utilized for the determination of the porosity of foamed concrete with different weight fractions of GGBS are depicted in Figure 3. The reduction in porosity of the foamed concrete mixtures was significant as the weight fractions of GGBS increased. This reduction was observed up to a cement replacement level of 30% with GGBS. The presence of GGBS particles in the pores at the interface between the binder paste and the filler resulted in a decrease in capillary pore activity. It is important to note that the pores were filled with GGBS inclusion. The observed trend in porosity values can be attributed to the alteration of the microstructure in the presence of GGBS, as previously discussed. GGBS is employed for the purpose of filling both discrete and continuous voids that are found within the specimens. The capillary suction responsible for the water absorption in the foamed concrete specimens is reduced by this phenomenon. The region of interface between fine sand and binder is characterized by the presence of a significant number of gel pores. When the pores were infiltrated by water, it is probable that a combination of water and air would occur at the interface. Cementitious materials are widely recognized for their capacity to facilitate the movement of water via capillaries, thereby inducing capillary action [59]. The formation of pores varies across different regions due to the influence of the interface and capillary action. The incorporation of GGBS leads to a decrease in the formation of these pore structures. The incorporation of GGBS facilitated the compaction of the microstructure of foamed concrete and decreased its porosity, specifically the interconnectivity of pores within the material [60]. The inclusion of GGBS in the mixture results in the refinement of the pore structure, leading to an enhancement in the impermeability of foamed concrete. However, when the GGBS replacement exceeded 30%, there was a significant increase in porosity. This can be attributed to the accumulation of GGBS particles in the cementitious matrix, resulting in a reduced ability to fill the air voids in the foamed concrete cementitious composite. Microfractures are formed within the matrix of foamed concrete at the interface zone due to the inclusion of GGBS, resulting in an increased dispersal transmission of water through these fractures.

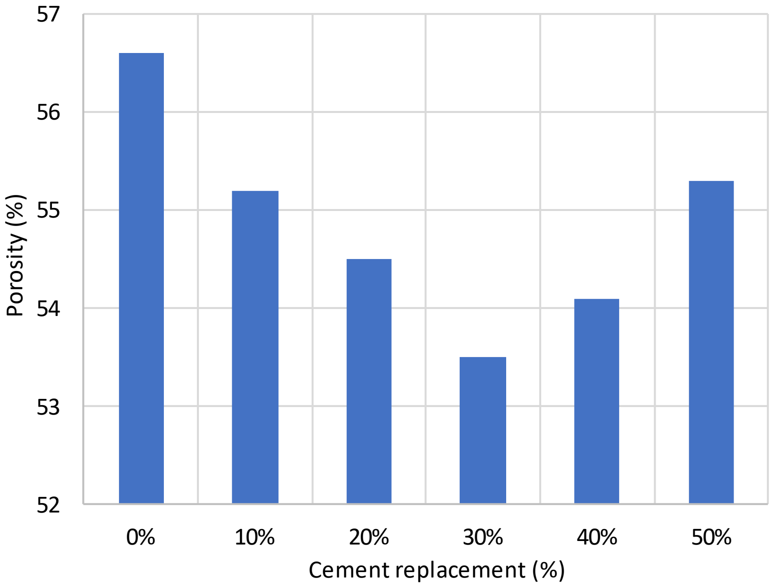

Fig. 3. Porosity of foamed concrete with various amounts of GGBS addition

3.3 Water Absorption

The water absorption behaviour of foamed concrete was utilized to determine the porosity of the material. The water permeability of foamed concrete was evaluated using this criterion. The total water absorption rate of foamed concrete is influenced by its porosity and compactness to a certain degree [61]. In the context of foamed concrete, it is important to note that high rates of water absorption can adversely impact the durability of harmful ions and solutes that have infiltrated the cementitious matrix through the pores, along with the water [62]. Figure 4 illustrates the test results pertaining to the water absorption of foamed concrete with different levels of GGBS cement replacement. Based on the findings presented in Figure 4, it was observed that the inclusion of GGBS in this study resulted in a decrease in the water absorption rate. The foamed concrete specimen, which had a 30% GGBS cement replacement, exhibited the lowest water absorption rate value. This value decreased by 15.2% when compared to the control specimen (GGBS-0). Based on the obtained results, it can be observed that the inclusion of GGBS in foamed concrete contributes to a reduction in water absorption. This improvement can be attributed to the enhanced microstructure achieved with the addition of GGBS. The formation of a seal between the gel pores within the mixture is attributed to the smaller particle size of the Ground Granulated Blast Furnace Slag (GGBS) in the foamed concrete mix [63]. This phenomenon can be attributed to the presence of refined pores and a densified microstructure on the surface. The incorporation of Ground Granulated Blast Furnace Slag (GGBS) resulted in an enhancement of the microstructure of foamed concrete, specifically by reducing the size and quantity of pores [64]. Moreover, it enhanced the cohesion between the cement matrix and the sand, resulting in a more durable foamed concrete. The water absorption capacity of foamed concrete increased when the proportion of GGBS used as a cement replacement exceeded 30%. This phenomenon can be attributed to the accumulation of GGBS, which subsequently reduces the material's ability to effectively fill voids.

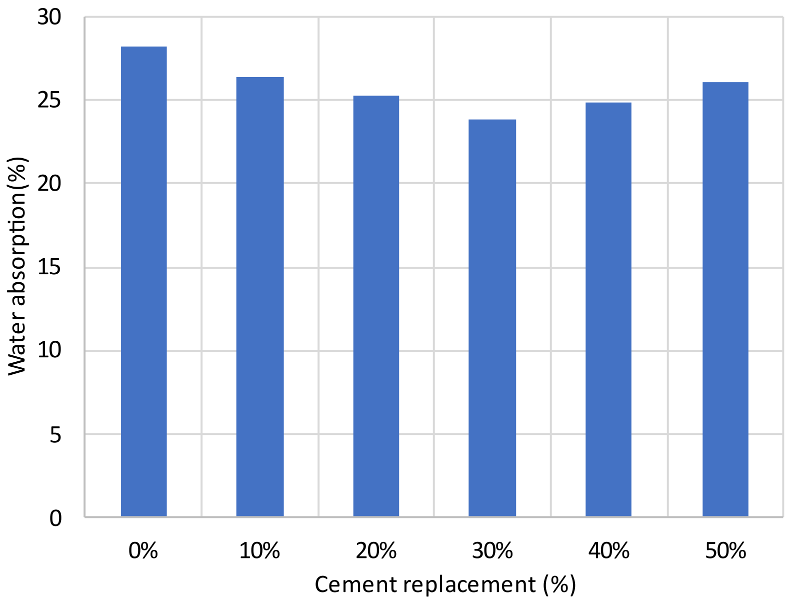

Fig. 4. Water absorption of foamed concrete with various amounts of GGBS addition

3.4 Thermal Conductivity

Figure 5 illustrates the outcomes pertaining to the thermal conductivity of foamed concrete, wherein various proportions of cement are substituted with GGBS. The findings of this study have provided confirmation that the incorporation of GGBS at various weight fractions resulted in enhanced thermal conductivity when compared to the control sample, which exhibited a thermal conductivity value of 0.2470 W/mK. The inclusion of 30% GGBS yielded the most favourable outcome in terms of thermal conductivity. The measured thermal conductivity was determined to be 0.2148 W/mK. In contrast, the thermal conductivity of the sample containing 40% cement replacement with GGBS was found to be higher when compared to the sample containing 30% GGBS. The non-uniform distribution of GGBS in foamed concrete may be attributed to the attainment of its optimal volume fraction, which is 30%. The decrease in thermal conductivity as the percentage of GGBS increases (up to the optimum percentage) can be attributed to the porous characteristics inherent in GGBS. Additional factors contributing to the significantly reduced thermal conductivity observed in foamed concrete composites include the redistribution of particles and the formation of smaller, more uniformly distributed pore voids as a result of the incorporation of GGBS. The inclusion of GGBS resulted in the formation of a greater number of isolated pore voids compared to the control group without GGBS addition. The findings of the study also indicate that GGBS exhibits significant potential for application in cement-based materials, such as foamed concrete. In this context, GGBS can effectively contribute to the reduction of thermal conductivity or heat transfer in the resulting concrete. Moreover, the utilization of GGBS in the production of foamed concrete offers potential energy-saving benefits, particularly in its application as a sustainable construction material [65]. One of the essential requirements for green building practices in Malaysia is the promotion of low energy consumption. Consequently, the utilization of this composite material in concrete precast walls or non-load-bearing structures can effectively enhance heat insulation properties compared to conventional foamed concrete. This improvement contributes to a reduction in energy consumption associated with temperature regulation within enclosed spaces.

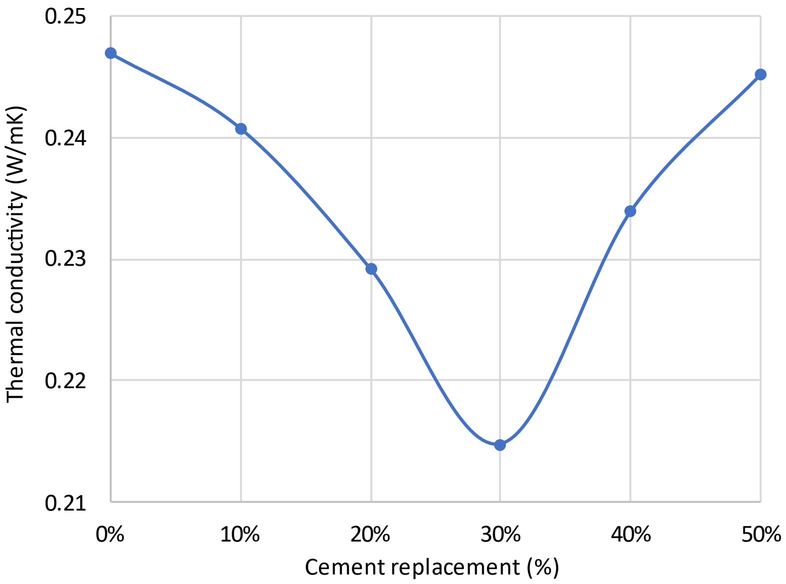

Fig. 5. Thermal conductivity of foamed concrete with various amounts of GGBS addition

3.5 Thermal Diffusivity

Figure 6 illustrates the thermal diffusivity outcomes of foamed concrete incorporating different proportions of GGBS as a substitute for cement. The data presented in Figure 6 demonstrates a significant decrease in thermal diffusivity as the proportion of GGBS increases. The thermal conductivity of the foamed concrete was determined as a result. As the percentage of GGBS in foamed concrete is increased from 10% to 20% and then to 30%, there is a corresponding decrease in thermal diffusivity. The values of thermal diffusivity for these GGBS percentages are 0.4365, 0.4281, and 0.4064 m^2/sec, respectively. The addition of GGBS to foamed concrete contributes to a decrease in thermal diffusivity due to the relatively low thermal conductivity exhibited by GGBS. The thermal diffusivity of foamed concrete can be characterized as the ratio of its thermal conductivity to its volumetric heat capacity. To clarify, the thermal diffusivity of foamed concrete refers to the rate at which heat is conducted within the composite material [66]. Therefore, if the rate of heat transfer within a composite material is high, the material can be classified as a highly efficient thermal conductor. On the other hand, when the rate of heat transfer within the material of a composite is significantly low, it is regarded as a highly effective thermal insulator. The incorporation of GGBS into foamed concrete results in an accelerated heat transfer rate, thereby conferring exceptional thermal insulation properties.

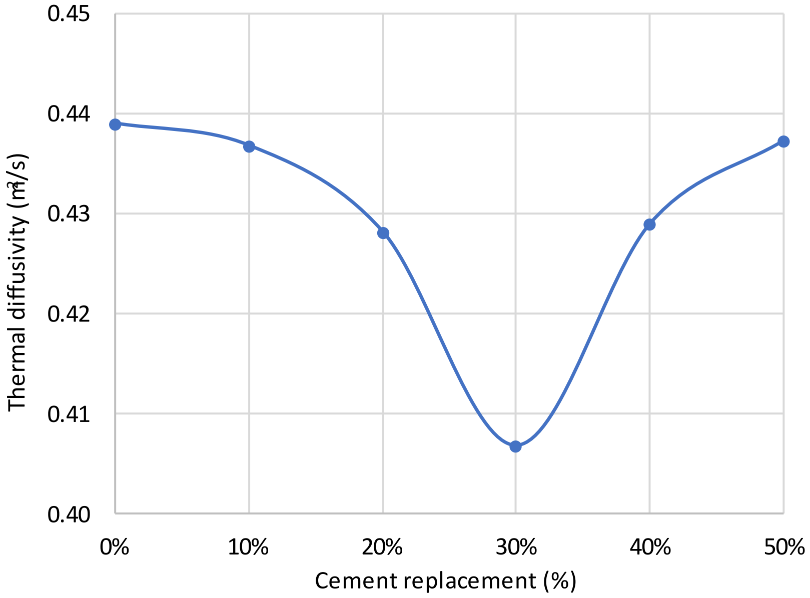

Fig. 6. Thermal diffusivity of foamed concrete with various amounts of GGBS addition

4. Conclusions

The objective of this study is to investigate the potential application of GGBS as a substitute for cement in foamed concrete, with the aim of enhancing its electrical conductivity and thermal characteristics. In this study, various proportions of GGBS ranging from 10% to 50% were incorporated into foamed concrete specimens with a density of 800 kg/m^3. The outcomes of these specimens were then compared to those of a control foamed concrete specimen. Multiple parameters were assessed, encompassing water absorption, porosity, electrical sensitivity, thermal diffusivity, and thermal conductivity. This study demonstrates that the incorporation of GGBS as a substitute for cement in foamed concrete plays a significant role in enhancing the characteristics of foamed concrete. The following conclusions can be inferred.

i. The GGBS-30 mixture demonstrated superior electrical resistivity in comparison to the other mixtures. The control mixture, specifically the one with ground granulated blast furnace slag (GGBS) content of 0%, exhibited the highest electrical resistivity. It is imperative to note that the electrical resistivity of GGBS-40 surpasses that of GGBS-30 after a period of 28 days. When comparing the two, it can be observed that the 28-day electrical resistivity of GGBS-50 demonstrates a greater magnitude in comparison to GGBS-40. The observed phenomenon can be ascribed to a greater degree of discontinuity in the pore structure of GGBS-40 in comparison to GGBS-30.

ii. The increase in weight fractions of GGBS resulted in a notable decrease in the porosity of the foamed concrete mixtures. The decrease in magnitude was noted until a substitution rate of 30% with GGBS was reached. The inclusion of GGBS particles within the pores located at the interface between the binder paste and the filler led to a reduction in the activity of capillary pores. It is imperative to acknowledge that the pores were effectively filled with GGBS inclusions. The alteration of the microstructure in the presence of GGBS can be identified as the underlying cause for the observed trend in porosity values.
iii. The incorporation of GGBS in the present investigation led to a reduction in the rate of water absorption. The water absorption rate of the foamed concrete specimen, which underwent a 30% replacement of GGBS cement, was found to be the lowest among the tested samples. The observed value exhibited a decrease of 15.2% in comparison to the control specimen, GGBS-0. The results obtained indicate that the addition of GGBS to foamed concrete leads to a decrease in water absorption. The observed enhancement can be ascribed to the improved microstructure attained through the incorporation of GGBS.
iv. The addition of GGBS led to an improvement in thermal conductivity compared to the reference sample, which had a thermal conductivity value of 0.2470 W/mK. The incorporation of 30% ground granulated blast furnace slag (GGBS) resulted in the most advantageous outcome in relation to thermal conductivity. The thermal conductivity measurement yielded a value of 0.2148 W/mK.
v. The experimental results indicate a notable reduction in thermal diffusivity with an increasing proportion of Ground Granulated Blast Furnace Slag (GGBS). The thermal conductivity of the foamed concrete was determined as an outcome. As the proportion of ground granulated blast furnace slag (GGBS) in foamed concrete is incrementally raised from 10% to 20% and subsequently to 30%, a concomitant reduction in thermal diffusivity is observed. The thermal diffusivity values for the various percentages of GGBS are 0.4365, 0.4281, and 0.4064 m2/sec, respectively.

Acknowledgment

This work is supported by the Ministry of Higher Education, Malaysia through the Fundamental Research Grant Scheme Grant Ref. No. FRGS/1/2022/TK01/USM/02/3

References

[1] Cunha, Sandra, Marisa Silva, and José Aguiar. "Behavior of cementitious mortars with direct incorporation of non-encapsulated phase change material after severe temperature exposure." *Construction and Building Materials* 230 (2020): 117011. https://doi.org/10.1016/j.conbuildmat.2019.117011
[2] Nawi, Mohd, Angela Lee, Md Azree Othman Mydin, Wan Nadzri Osman, and Mohamad Khadafi Rofie. "Supply chain management (SCM): disintegration team factors in Malaysian industrialised building system (IBS) construction projects." *International Journal of Supply Chain Management* 7, no. 1 (2018).
[3] Ürge-Vorsatz, Diana, Luisa F. Cabeza, Susana Serrano, Camila Barreneche, and Ksenia Petrichenko. "Heating and cooling energy trends and drivers in buildings." *Renewable and Sustainable Energy Reviews* 41 (2015): 85-98. https://doi.org/10.1016/j.rser.2014.08.039
[4] Mydin, MA Othuman, A. F. Phius, N. Md Sani, and Norngainy Mohd Tawil. "Potential of green construction in Malaysia: industrialised building system (IBS) vs traditional construction method." In *E3S Web of Conferences*, vol. 3, p. 01009. EDP Sciences, 2014. https://doi.org/10.1051/e3sconf/20140301009
[5] Li, Shuang-Fei, Zhen-hua Liu, and Xue-Jiao Wang. "A comprehensive review on positive cold energy storage technologies and applications in air conditioning with phase change materials." *Applied Energy* 255 (2019): 113667. https://doi.org/10.1016/j.apenergy.2019.113667
[6] Mydin, MA Othuman, N. Md Sani, and A. F. Phius. "Investigation of industrialised building system performance in comparison to conventional construction method." In *MATEC Web Of Conferences*, vol. 10, p. 04001. EDP Sciences, 2014. https://doi.org/10.1051/matecconf/20141004001

[7] Esruq-Labin, A. M. J., Adi Irfan Che-Ani, N. M. Tawil, Mohd Nasrun Mohd Nawi, and Othuman Mydin. "Criteria for affordable housing performance measurement: a review." In *E3S web of conferences*, vol. 3. EDP Sciences, 2014. https://doi.org/10.1051/e3sconf/20140301003

[8] Saffari, Mohammad, Cristina Piselli, Alvaro De Gracia, Anna Laura Pisello, Franco Cotana, and Luisa F. Cabeza. "Thermal stress reduction in cool roof membranes using phase change materials (PCM)." *Energy and Buildings* 158 (2018): 1097-1105. https://doi.org/10.1016/j.enbuild.2017.10.068

[9] Mydin, MA Othuman, J. C. Khor, and N. Md Sani. "Approaches to construction waste management in Malaysia." In *MATEC Web of Conferences*, vol. 17, p. 01014. EDP Sciences, 2014. https://doi.org/10.1051/matecconf/20141701014

[10] Faraj, Khaireldin, Mahmoud Khaled, Jalal Faraj, Farouk Hachem, and Cathy Castelain. "Phase change material thermal energy storage systems for cooling applications in buildings: A review." Renewable and Sustainable Energy Reviews 119 (2020): 109579. https://doi.org/10.1016/j.rser.2019.109579

[11] Ganesan, Shankar, Md Azree Othuman Mydin, Norazmawati Md Sani, and Adi Irfan Che Ani. "Performance of polymer modified mortar with different dosage of polymeric modifier." In *MATEC Web of Conferences*, vol. 15, p. 01039. EDP Sciences, 2014. https://doi.org/10.1051/matecconf/20141501039

[12] Elshahawi, Mahmoud, Alex Hückler, and Mike Schlaich. "Infra lightweight concrete: A decade of investigation (a review)." *Structural Concrete* 22 (2021): E152-E168. https://doi.org/10.1002/suco.202000206

[13] Tambichik, Muhammad Afiq, Abdul Aziz Abdul Samad, Noridah Mohamad, Ahmad Zurisman Mohd Ali, Md Azree Othuman Mydin, Mohamad Zulhairi Mohd Bosro, and Muhamad Afif Iman. "Effect of combining Palm Oil Fuel Ash (POFA) and Rice Husk Ash (RHA) as pozzolan to the compressive strength of concrete." *International Journal of Integrated Engineering* 10, no. 8 (2018). https://doi.org/10.30880/ijie.2018.10.08.004

[14] Mydin, MA Othuman, MF Mohamed Shajahan, S. Ganesan, and N. Md Sani. "Laboratory investigation on compressive strength and micro-structural features of foamed concrete with addition of wood ash and silica fume as a cement replacement." In *MATEC Web of Conferences*, vol. 17, p. 01004. EDP Sciences, 2014. https://doi.org/10.1051/matecconf/20141701004

[15] Sukontasukkul, Piti, Pattra Uthaichotirat, Teerawat Sangpet, Kritsada Sisomphon, Moray Newlands, Anek Siripanichgorn, and Prinya Chindaprasirt. "Thermal properties of lightweight concrete incorporating high contents of phase change materials." *Construction and Building Materials* 207 (2019): 431-439. https://doi.org/10.1016/j.conbuildma t.2019.02.152

[16] Awang, Hanizam, Md Azree Othuman Mydin, and Ahmad Farhan Roslan. "Effects of fibre on drying shrinkage, compressive and flexural strength of lightweight foamed concrete." *Advanced Materials Research* 587 (2012): 144-149. https://doi.org/10.4028/www.scientific.net/AMR.587.144

[17] Mydin, MA Othuman, N. Mohd Zamzani, and AN Abdul Ghani. "Experimental data on compressive and flexural strengths of coir fibre reinforced foamed concrete at elevated temperatures." *Data in brief* 25 (2019): 104320. https://doi.org/10.1016/j.dib.2019.104320

[18] Brady, K. C., G. R. A. Watts, and M. Roderick Jones. *Specification for foamed concrete*. Crowthorne, UK: TRL Limited, 2001.

[19] Amran, YH Mugahed, Nima Farzadnia, and AA Abang Ali. "Properties and applications of foamed concrete; a review." *Construction and Building Materials* 101 (2015): 990-1005. https://doi.org/10.1016/j.conbuildmat.2015.10.112

[20] Nensok, Mohammed Hassan, Md Azree Othuman Mydin, and Hanizam Awang. "Investigation of thermal, mechanical and transport properties of ultra-lightweight foamed concrete (ULFC) strengthened with alkali treated banana fibre." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 86, no. 1 (2021): 123-139. https://doi.org/10.37934/arfmts.86.1.123139

[21] Serri, E., MA Othuman Mydin, and M. Z. Suleiman. "The influence of mix design on mechanical properties of oil palm shell lightweight concrete." *J. Mater. Environ. Sci* 3 (2015): 607-612.

[22] Othuman Mydin, M. A., and N. Mohd Zamzani. "Coconut fiber strengthen high performance concrete: Young's modulus, ultrasonic pulse velocity and ductility properties." *International Journal of Engineering and Technology (UAE)* 7, no. 2 (2018): 284-287. https://doi.org/10.14419/ijet.v7i2.23.11933

[23] Suhaili, Siti Shahirah, Md Azree Othuman Mydin, and Hanizam Awang. "Influence of mesocarp fibre inclusion on thermal properties of foamed concrete." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 87, no. 1 (2021): 1-11. https://doi.org/10.37934/arfmts.87.1.111

[24] Nensok, Mohammed Hassan, Md Azree Othuman Mydin, and Hanizam Awang. "Fresh state and mechanical properties of ultra-lightweight foamed concrete incorporating alkali treated banana fibre." *Jurnal Teknologi* 84 (2022): 117-128. https://doi.org/10.11113/jurnalteknologi.v84.16892

[25] Valore Jr, R. C. "Cellular concretes Part 2 physical properties, ACI J." *Proc. 50 (6)* (1954).

[26] Ramamurthy, K., EK Kunhanandan Nambiar, and G. Indu Siva Ranjani. "A classification of studies on properties of foam concrete." *Cement and concrete composites* 31, no. 6 (2009): 388-396. https://doi.org/10.1016/j.cemconcomp.2009.04.006

[27] Mydin, M. A., N. Mohd Zamzani, and A. N. Ghani. "Effect of alkali-activated sodium hydroxide treatment of coconut fiber on mechanical properties of lightweight foamed concrete." In *AIP Conference Proceedings*, vol. 2016, no. 1. AIP Publishing, 2018. https://doi.org/10.1063/1.5055510

[28] Mydin, M. A., N. Mohamad, A. A. Samad, I. Johari, and M. A. Munaaim. "Durability performance of foamed concrete strengthened with chemical treated (NaOH) coconut fiber." In *AIP Conference Proceedings*, vol. 2016, no. 1. AIP Publishing, 2018. https://doi.org/10.1063/1.5055511

[29] Mydin, Md Azree Othuman, Mohd Nasrun Mohd Nawi, Muhammad Arkam Che Munaaim, Noridah Mohamad, Abdul Aziz Abdul Samad, and Izwan Johari. "Effect of steel fibre volume fraction on thermal performance of Lightweight Foamed Mortar (LFM) at ambient temperature." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 47, no. 1 (2018): 119-126.

[30] Jones, M. R., and A. McCarthy. "Preliminary views on the potential of foamed concrete as a structural material." *Magazine of concrete research* 57, no. 1 (2005): 21-31. https://doi.org/10.1680/macr.2005.57.1.21

[31] Richard, T., Joseph Dobogai, T. Gerhardt, and W. Young. "Cellular concrete-A potential load-bearing insulation for cryogenic applications?." *IEEE Transactions on Magnetics* 11, no. 2 (1975): 500-503. https://doi.org/10.1109/TMAG.1975.1058746

[32] Serudin, Anisah Mat, Md Azree Othuman Mydin, and Abdul Naser Abdul Ghani. "Influence of Fibreglass Mesh on Physical Properties of Lightweight Foamcrete." *IIUM Engineering Journal* 22, no. 1 (2021): 23-34. https://doi.org/10.31436/iiumej.v22i1.1446

[33] Musa, M., and Othuman Mydin. "MA; Abdul Ghani, AN Influence of oil palm empty fruit bunch (EFB) fibre on drying shrinkage in restrained lightweight foamed mortar." *Int. J. Innov. Technol. Exp. Eng* 8 (2019): 4533-4538. https://doi.org/10.35940/ijitee.J1080.0881019

[34] Zamzani, N. M., M. A. O. Mydin, and A. N. A. Ghani. "Effectiveness of 'cocos nucifera linn'fibre reinforcement on the drying shrinkage of lightweight foamed concrete." *ARPN J. Eng. Appl. Sci* 14 (2019): 3932-3937.

[35] Mydin, Md Azree Othuman, Shankar Ganesan, Mohd Yazid Mohd Yunos, Nangkula Utaberta, and Nor Atiah Ismail. "Structural behaviour of coir fibre-reinforced foamed concrete wall panel system." *J. Teknol* 78, no. 5 (2016): 169-177. https://doi.org/10.11113/jt.v78.8276

[36] Serudin, Anisah Mat, Md Azree Mydin Othuman, and Abdul Naser Abdul Ghani. "Effect of lightweight foamed concrete confinement with woven fiberglass mesh on its drying shrinkage." (2021). https://doi.org/10.4067/S0718-50732021000100021

[37] Mohd Zamzani, N., and Othuman Mydin. "MA; Abdul Ghani, AN Influence of 'Cocos Nucifera Linn'fiber volume fraction on water absorption and porosity of foamed concrete." *Int. J. Eng. Adv. Technol* 8 (2019): 3428-3435. https://doi.org/10.35940/ijeat.F9514.088619

[38] Mohd Zamzani, N. , Othuman Mydin, M.A. , Abdul Ghani, A.N. Mathematical regression models for prediction of durability properties of foamed concrete with the inclusion of coir fibre. International Journal of Engineering and Advanced Technology, 2019, 8(6): 3353-3358. https://doi.org/10.35940/ijeat.F9502.088619

[39] Mydin, MA Othuman. "Evaluation of splitting tensile strength in plain and fibre-reinforced foamed mortar." *Jurnal Teknologi* 78, no. 5 (2016): 413-419. https://doi.org/10.11113/jt.v78.8346

[40] Hassan Nensok, Mohammed, Md Azree Othuman Mydin, and Hanizam Awang. "Optimization of mechanical properties of cellular lightweight concrete with alkali treated banana fiber." *Revista de la construcción* 20, no. 3 (2021): 491-511. https://doi.org/10.7764/RDLC.20.3.491

[41] Tikalsky, Paul J., James Pospisil, and William MacDonald. "A method for assessment of the freeze–thaw resistance of preformed foam cellular concrete." *Cement and concrete research* 34, no. 5 (2004): 889-893. https://doi.org/10.1016/j.cemconres.2003.11.005

[42] Suhaili, S. S., and M. A. O. Mydin. "Potential of stalk and spikelets of empty fruit bunch fibres on mechanical properties of lightweight foamed concrete." *Int J Sci Technol Res* 9, no. 3 (2020): 3199-3204.

[43] Weigler, Helmut, and Sieghart Karl. "Structural lightweight aggregate concrete with reduced density—lightweight aggregate foamed concrete." *International Journal of Cement Composites and Lightweight Concrete* 2, no. 2 (1980): 101-104. https://doi.org/10.1016/0262-5075(80)90029-9

[44] Zamzani, Nabihah Mohd, Azree Othuman Mydin, and Abdul Naser Abdul Ghani. "Experimental investigation on engineering properties of lightweight foamed concrete (LFC) with coconut fiber addition." In *MATEC Web of Conferences*, vol. 250, p. 05005. EDP Sciences, 2018. https://doi.org/10.1051/matecconf/201825005005

[45] Beningfield, N., R. Gaimster, and P. Griffin. "Investigation into the air void characteristics of foamed concrete." In *Use of Foamed Concrete in Construction: Proceedings of the International Conference held at the University of Dundee, Scotland, UK on 5 July 2005*, pp. 51-60. Thomas Telford Publishing, 2005.

[46] Othuman Mydin, Md Azree, Mohd Nasrun Mohd Nawi, Ruba A. Odeh, and Anas A. Salameh. "Durability Properties of Lightweight Foamed Concrete Reinforced with Lignocellulosic Fibers." *Materials* 15, no. 12 (2022): 4259. https://doi.org/10.3390/ma15124259

[47] Turner, M. "Fast set foamed concrete for same day reinstatement of openings in highways." In *Proceedings of One Day Seminar on Foamed Concrete: Properties, Applications and Latest Technological Developments*, pp. 12-18. Loughborough University, 2001.

[48] Mydin, Md Azree Othuman, Mohd Nasrun Mohd Nawi, Muhammad Arkam Che Munaaim, and Othman Mohamed. "A Study on the influence of oil palm trunk fiber on ultrasonic pulse velocity (UPV) and shrinkage of foamcrete." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 76, no. 2 (2020): 111-117. https://doi.org/10.37934/arfmts.76.2.111117

[49] Othuman Mydin, M. A. "Potential of natural and synthetic fibres on flexural performance of foamcrete mortar." *Jurnal Teknologi* 78, no. 5: 431-435. https://doi.org/10.11113/jt.v78.8348

[50] Mindess, Sidney, ed. *Developments in the Formulation and Reinforcement of Concrete*. Woodhead Publishing, 2019.

[51] Othuman Mydin, Md Azree, Mohd Nasrun Mohd Nawi, Othman Mohamed, and Marti Widya Sari. "Mechanical Properties of Lightweight Foamed Concrete Modified with Magnetite (Fe3O4) Nanoparticles." *Materials* 15, no. 17 (2022): 5911. https://doi.org/10.3390/ma15175911

[52] Othuman, Azree, Anisah Mat Serudin, and Abdul Naser Abdul Ghani. "Investigating the load carrying capacities of lightweight foamed concrete strengthen with fiber mesh." *International Journal of Integrated Engineering* 14, no. 4 (2022): 360-376. https://doi.org/10.30880/ijie.2022.14.04.028

[53] Durack, J. M., and L. Weiqing. "The properties of foamed air cured fly ash based concrete for masonry production." In *Proceedings of the fifth Australasian masonry conference*, pp. 129-38. Gladstone The Queensland, Australia, 1998.

[54] Mydin, MA Othuman. "Effect of silica fume and wood ash additions on flexural and splitting tensile strength of lightweight foamed concrete." *Jurnal Teknologi* 74, no. 1 (2015): 125-129. https://doi.org/10.11113/jt.v74.3653

[55] Mydin, Md Azree Othuman. "The effect of raw mesocarp fibre inclusion on the durability properties of lightweight foamed concrete." *ASEAN Journal on Science and Technology for Development* 38, no. 2 (2021): 59-66. https://doi.org/10.29037/ajstd.685

[56] Newlands, Moray D., M. Rod Jones, Sivakumar Kandasami, and Tom A. Harrison. "Sensitivity of electrode contact solutions and contact pressure in assessing electrical resistivity of concrete." *Materials and structures* 41 (2008): 621-632. https://doi.org/10.1617/s11527-007-9257-6

[57] Spragg, Robert P., J. Castro, Tommy E. Nantung, M. Paredes, and W. Jason Weiss. "Variability analysis of the bulk resistivity measured using concrete cylinders." (2011). https://doi.org/10.5703/1288284314646

[58] McCarter, W. John, Gerry Starrs, Siva Kandasami, Rod Jones, and Malcolm Chrisp. "Electrode configurations for resistivity measurements on concrete." *ACI materials journal* 106, no. 3 (2009): 258. https://doi.org/10.14359/56550

[59] De Rose, L., and J. Morris. *The influence of mix design on the properties of microcellular concrete*. Thomas Telford: London, UK, 1999. https://doi.org/10.1680/stamfcc.28258.0018

[60] Pickford, C., and S. Crompton. "Foamed concrete in bridge construction." *Concrete* 30, no. 6 (1996).

[61] Ibrahim, Norlia Mohamad, Roshazita Che Amat, Nur Liza Rahim, and Shamshinar Sallehuddin. "Performance of lightweight foamed concrete with replacement of concrete sludge aggregate as coarse aggregate." *Advanced Materials Research* 689 (2013): 265-268. https://doi.org/10.4028/www.scientific.net/AMR.689.265

[62] Wee, Tiong-Huan, Daneti Saradhi Babu, T. Tamilselvan, and Hwee-Sin Lim. "Air-void system of foamed concrete and its effect on mechanical properties." *ACI materials journal* 103, no. 1 (2006): 45. https://doi.org/10.14359/15126

[63] Ruiwen, Kong. "Properties of high-strength foam concrete." (2004).

[64] M.R. Jones, Foamed concrete for structural use, in: Proceedings of One Day Seminar on Foamed Concrete: Properties, Applications and Latest Technological Developments, Loughborough University, 2001, pp. 27–60.

[65] Mydin, MA Othuman, N. A. Rozlan, N. Md Sani, and S. Ganesan. "Analysis of micro-morphology, thermal conductivity, thermal diffusivity and specific heat capacity of coconut fibre reinforced foamed concrete." In *MATEC Web of Conferences*, vol. 17, p. 01020. EDP Sciences, 2014. https://doi.org/10.1051/matecconf/20141701020

[66] Mydin, Md Azree Othuman. "Assessment of thermal conductivity, thermal diffusivity and specific heat capacity of lightweight aggregate foamed concrete." *Jurnal teknologi* 78, no. 5 (2016). https://doi.org/10.11113/jt.v78.8374