

Effect of Carbonic Acid as Water Replacement Material on the Thermal Conductivity of Lightweight Foamed Concrete Block

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ABSTRACT

Cement production's rising emissions of greenhouse gases, especially CO₂, are a major cause of environmental alarm. Concerning that, this study examines the effects of carbonic acid on Lightweight Foamed Concrete Blocks (LFCB), with an emphasis on its density and thermal properties. It aims to investigate the impact of different carbonic acid concentrations on the density and thermal conductivity of LFCB, as well as the relationship between these variables. Modest levels of carbonic acid appear to promote the growth and connection of carbonate crystals in the concrete matrix, which, in effect, creates a less porous material and insulating ability. Higher concentrations result in larger pore sizes and structural changes that can generate higher thermal conductive materials. The carbonic acid shows as a derivation of density and thermal conductivity (principally till 50%) when there is an optimal density for normal LFCB blocks. Meanwhile, at this stage of concentration, it can lead to an increase in density and thermal conductivity. The results aim to fill the knowledge gap for the construction behaviour of LFCB as a material and provide a reference for future research on carbon neutrality in buildings.

Keywords: Lightweight concrete; foamed concrete; concrete block; carbonic acid; thermal conductivity

INTRODUCTION

Among the challenges is the increasing concentration of greenhouse gases in the atmosphere, primarily carbon dioxide (CO₂), a byproduct among others from industrial activities like cement production. The production of cement is one of the main contributors to global CO₂ emissions, which takes place not only during the calcination process but also through the hydration of cement in traditional concrete curing (Habert et al. 2020). This dual-source emission underscores the urgent need for long-term, sustainable alternatives that can counterbalance the environmental consequences of construction materials. Addressing this challenge requires innovative strategies that reduce CO₂ emissions while simultaneously improving the performance of construction materials.

A novel and more futuristic approach involves the adoption of carbon capture and utilization (CCU) technologies. These technologies enable the capture of CO₂ emissions from industrial processes for reuse in material production, thereby transforming waste gases into valuable inputs. One promising approach is to incorporate captured CO₂ into concrete production to create carbonic acid (H₂CO₃), a compound that can significantly influence the material's properties. The recycling of captured CO₂ into carbonic acid for concrete production appears to be a very environmentally friendly method for reducing pollution and improving the physical properties of concrete (Liang et al. 2023). This process not only supports sustainable development but also aligns with global decarbonization goals aimed at reducing the overall carbon footprint of the construction industry.

Some studies have considered the use of carbonic acid (H_2CO_3), formed by adding CO_2 to water, as a potential alternative in concrete mixes instead of using only water. The advantage of this method is that it enhances the carbonation reactions in the cement matrix, where one of its products is calcium carbonate (CaCO_3), a compound that enhances the durability and thermal conductivity of the material (Shah et al. 2021). The formation of CaCO_3 within the cement matrix contributes to the densification of the microstructure, improving its resistance to environmental degradation and moisture ingress. Although these are promising results, the effect of carbonic acid on the porosity and thermal conductivity of lightweight foamed concrete blocks (LFCB) is still poorly understood. Filling this gap of knowledge might provide a novel path to boost the thermal resistance of LFCB and promote sustainable construction initiatives. This knowledge will be crucial for designing energy-efficient, low-carbon building materials that support green building certifications and sustainability goals.

Lightweight foamed concrete blocks (LFCB) are cementitious materials with a homogenous air void system created by the injection of stable foam. Air spaces reduce the density of the material, which generally ranges between 400 and 1850 kg/m^3 , making it an ideal candidate for energy-efficient construction (Amran et al. 2015). The lower density and weight of the material, together with improved energy efficiency, have led to elevated interest from the construction industry in LFCB. Reduced weight not only simplifies construction logistics but also lowers transportation and handling costs. However, many other factors can influence the thermal performance of LFCB, such as moisture level, density, and pore structure properties. The moisture level significantly affects the thermal conductivity of LFCB, diminishing its insulation efficiency (Asadi et al. 2018). As a result, addressing the effects of carbonic acid on LFCB's porosity and thermal conductivity has the potential to yield new insights into how this innovative approach can be used to develop sustainable and thermally efficient building materials.

Hore & Shiuly (2023) also showed through an experiment that the conventional concrete rate at which carbonation will cause deterioration of their durability and strength, as well as CO_2 , creates an acidic environment leading to speed up this process. This evidence highlights the importance of controlled carbonation in concrete, where carbonic acid may improve concrete properties by promoting beneficial carbonation reactions. These reactions lead to the formation of calcium carbonate, which enhances the thermal and durability performance of the concrete material (Ta et al. 2023). Such effects underscore the potential of using carbonic acid in LFCB production to promote higher durability and thermal resistance. While

these potentialities are promising, little research has been conducted on the influence of carbonic acid on the porosity, microstructure, and thermal conductivity of LFCB. Filling this research gap is essential for enhancing the broader applicability of LFCB in modern construction projects focused on sustainability.

The present research has three main aims: to examine the influence of varying the concentration of carbonic acid on the porosity of LFCB, to assess the impact of several percentages of carbonic acid on thermal conductivity in LFCB, and to establish a correlation between thermal conductivity and porosity in LFCB. Achieving these objectives will provide a comprehensive understanding of how carbonic acid can be used to improve the performance of LFCB, with a particular focus on its thermal efficiency and durability. These findings are expected to contribute to the development of next-generation, low-carbon construction materials that align with sustainability objectives. Ultimately, this research aims to support global efforts to reduce the construction industry's carbon footprint and promote sustainable development by encouraging the use of green construction materials.

METHODOLOGY

MATERIALS AND SPECIMEN PREPARATION

Lightweight foamed concrete block (LFCB) was prepared using water, carbonic acid, fine aggregates (sand), ordinary Portland cement (OPC), and a synthetic foaming agent that conformed to BS EN 197-1:2000. The carbonic acid in question was produced by bubbling controlled amounts of carbon dioxide (CO_2) through water. Carbonic acid solutions of different concentrations ranging from 0 % (control) up to 100 % were introduced into the water, and their effects on the microstructure and thermal conductivity of LFCB were assessed. The preparation was a gas dissolution procedure in which CO_2 was added to deionised water until the desired concentration. The solution of carbonic acid was then sealed away to prevent any loss of CO_2 before it was added to the concrete formulation.

The synthetic-based detergent acted as a foaming agent known to produce stable foam and provide a uniform distribution of air voids into the concrete matrix. The foaming agent was mixed with the water and incorporated into the cementitious slurry to create a lightweight foam structure. The steel moulds of 60 mm × 100 mm × 500 mm were used to cast the concrete blocks. A total of 10 LFCB samples having the same dimensions were prepared to ensure uniformity in thermal conductivity and other physical properties measurements. The parameters of each

specimen which was tested were also cured using different curing methods and time to study its effect on the thermal performance of the LFCB and the mechanical behaviour.

MIX DESIGN

This research uses two types of concrete mixtures. The initial mix was prepared with a typical composition containing Ordinary Portland Cement (OPC), sand, water, and stable foam. This mixture serves as the control, representing conventional lightweight foamed concrete block (LFCB) production. The second set of mixtures was

prepared with carbonic acid (CA) as a partial water replacement and consisted of OPC, sand, carbonic acid, water, and stable foam. The preparation of both mixtures was in accordance with the specifications of the Public Works Department of Malaysia (JKR 20800-0183-14) for concrete mix design. This adherence ensures the production of concrete blocks with consistent quality and structural performance. Furthermore, adherence to the British Standard (BS 1881: Part 125) for the mixing and sampling of fresh concrete was maintained to ensure reliability and consistency during the mixing process. These standards guarantee the repeatability of results and allow for comparisons across different experimental batches.

TABLE 1. LFCB mixture proportions

Mix	Sand (kg)	OPC (kg)	CA (kg)	Water (kg)	Foam
M1 (Control)	9.41	6.27	0	3.14	1:20
M2	9.41	6.27	0.78	2.36	1:20
M3	9.41	6.27	1.57	1.57	1:20
M4	9.41	6.27	2.36	0.78	1:20
M5	9.41	6.27	3.14	0	1:20

TABLE 2. Carbonic acid concentrations-to- water ratio

Sample no	Percentage of water (%)	Percentage of carbonic acid (%)
M1 (Control)	100	0
M2	75	25
M3	50	50
M4	25	75
M5	0	100

The experimental mix design is presented in Table 1, which specifies the mixture proportions for the LFCB blocks. Five mixtures were prepared independently by changing the water-to-CA ratio whilst keeping all other constituents constant. This variation was fundamental to determining the effect of CA concentration on the thermal characteristics of LFCB. The water-to-CA ratios were selected to capture a range of concentration levels, enabling a more comprehensive analysis of their influence on thermal performance. Table 2 presents the mixture of water to CA ratios for each LFCB mix. This allowed for a thorough investigation of the effects of varying concentrations on the material's thermal conductivity, as the CA concentrations varied from 0% (control) to 100%. By examining this range, the research aims to establish a clear understanding of the concentration threshold at which thermal conductivity is optimized. Additionally, this systematic approach allows for the identification of optimal CA concentrations that balance enhanced thermal conductivity with cost and sustainability considerations.

EXPERIMENTAL SETUP

Figure 1 displays the design of the hot box testing setup, which was developed to establish a controlled heating environment. The configuration, comprising a hot and cold chamber, was essential for evaluating the thermal conductivity of the LFCB blocks. The hot chamber sustained a constant temperature through the use of a heating wire, whereas the cold chamber was kept at ambient temperature. The arrangement of temperature sensors and heat flux sensors facilitated precise measurement of thermal conductivity in accordance with the standards established by BS EN ISO 8990:1996. During testing, the temperature in the hot chamber was maintained at 30°C with a heating wire that did not exceed 50 watts. The R-LOG data logger was developed with features tailored for specific inputs and measurements related to environmental sensors.



FIGURE 1. Hot box testing setup

Measurements of thermal conductivity were recorded using the LSI Lastem-created R-LOG data logger, which is shown in Figure 2. This multi-channel data logger is engineered to interface with environmental sensors, facilitating accurate data acquisition during hot box tests. In addition, Figure 3 illustrates that the cold chamber was outfitted with a heat flux sensor and temperature sensors positioned on the specimen surface and within the chamber air. This configuration assisted precise measurement of heat transfer from the cold to the hot side of the LFCB blocks. A heat-flux sensor was installed to quantify the heat flux across the LFCB plate, from the cold side to the hot

side. The object was located at the centre of the plate, with the red surfaces orientated towards the cold side of the LFCB plate. The measurement site included two surface temperature sensors and two air temperature sensors. Each side was equipped with one surface temperature sensor on the plate and one air temperature sensor suspended within both compartments. All multi-sensors were connected to a multi-channel data logger, R-LOG from LSI Lastem, for data acquisition recording. The measurement was performed over 3 hours, as specified in BS EN ISO 8990:1996, with data collected at 10-minute intervals.

Figure 4 shows the hot chamber with the same sensor locations used to monitor air and surface temperatures on the hot side of the LFCB blocks. This setup enabled accurate measurement of the temperature difference across the concrete samples.

The thermal conductivity value was determined using Equation (1).

$$\text{Thermal conductivity, } k = W/A[1 \times d/\Delta T] \tag{1}$$

Where W is the main heat tube electrical power, A is the surface area of the specimen, d is the thickness of the specimen, and ΔT is the surface temperature difference between the hot and cold chamber.



FIGURE 2. R-LOG data logger by LSI Lastem

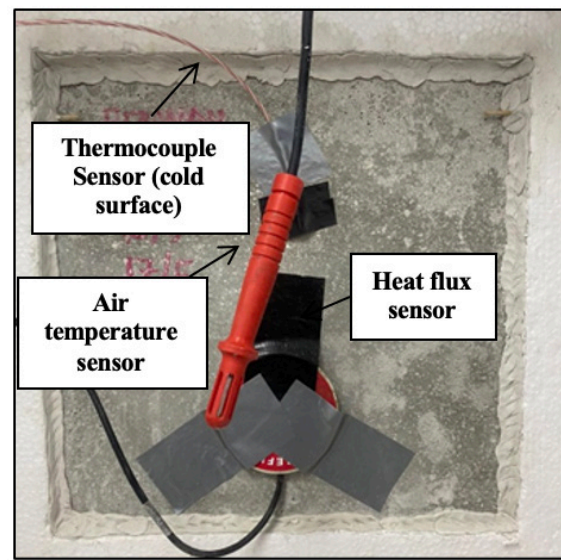


FIGURE 3. Cold chamber sensor arrangement on the specimen surface

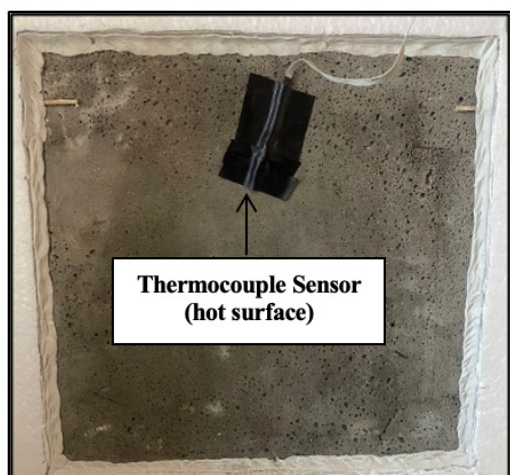


FIGURE 4. Hot chamber sensor arrangement on the specimen surface

RESULTS AND DISCUSSION

This section discusses the results from laboratory experiments on the thermal conductivity of (LFCB) blocks. It addresses the effect of carbonation and curing conditions on thermal conductivity, highlighting the need for optimisation of these variables towards energy saving. This section is further expanded with the influence of different carbonic acid concentrations and curing methods on the characteristics and thermal behaviour of the block in addition to thermal conductivity-density correlations.

THERMAL CONDUCTIVITY OF LFCB BLOCKS AND THE EFFECT OF DIFFERENT CARBONIC ACID CONCENTRATIONS ON THE PROPERTIES

Figure 5 shows the relationship of carbonic acid concentration with thermal conductance under standard curing conditions. Table 3 presents the relation between thermal conductivity and carbonic acid without or with concentration. The results of the observed variations in thermal conductivity demonstrate a crucial effect of carbonic acid concentration on the thermal properties of LFCB. The thermal conductivity of the M1 (control sample) dropped from 1.340 W/m°C at 28 days. For Sample M2, its thermal conduction value showed a decrease from 1.884 at 28days, while M3’s thermal conductivity rate has slight reduction value contributions of then reasonably higher at 2.081 W/m°C over the same period restrictions. The thermal conductivities of the samples M4 and M5 increased with increasing carbonic acid concentrations, likely due the compaction and consolidation effect of elevated ex-post carbonation doses, as demonstrated in

previous studies (Ta et al. 2023; Zhang et al. 2024).

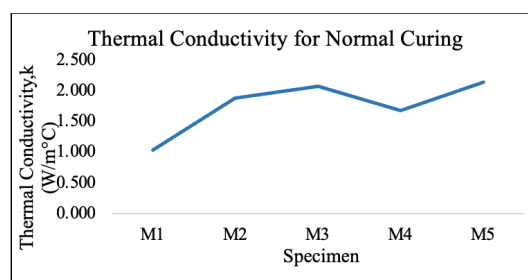


FIGURE 5. Thermal conductivity vs carbonic acid concentration for normal curing

TABLE 3. Thermal conductivity of LFCB with different Carbonic acid concentrations for normal curing methods

Sample	Thermal Conductivity, k (W/m°C)
M1	1.038
M2	1.884
M3	2.081
M4	1.687
M5	1.146

This pattern is in line with findings by Ta et al. (2023), indicating that moderate contents of carbonic acid promote the growth in the volume of carbonate crystals in the concrete matrix. Since the crystals can fill the pores, this should result in reduced porosity and, therefore, enhanced insulation. Modifications of thermal conductivity behaviour with an increase in pore size or other structural alterations (Samples M4 and M5) may be triggered by higher concentrations. In sample M4, the thermal conductivity increased gradually over time and was accompanied by an absorption peak of carbonic acid that could interact with the concrete matrix. The largest increase was observed for sample M5, which would seem to indicate that too high a carbonate concentration could reduce the insulation properties of the material.

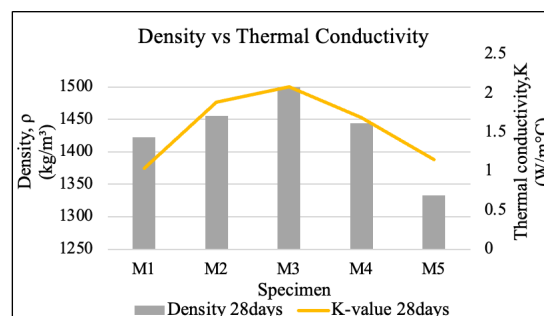


FIGURE 6. Density and thermal conductivity of LFCB on different carbonic acid concentrations for normal curing

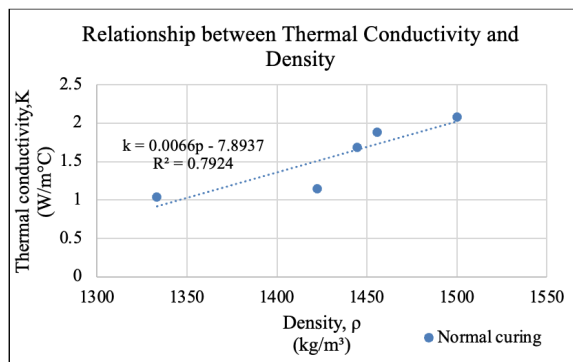


FIGURE 7. Correlation between thermal conductivity and density

The microstructural of LFCB was influenced by the thermal conductivity differences in carbonic acid, allowing calcium carbonate crystals to form the pores and microcracks. At 2–3% volume concentration (Samples M2 and M3), such crystals reduce porosity to a level that the thermal conductivity is also reduced so that the insulation functionality of the material is increased greatly. Earlier studies (Ta et al. 2023; Hore & Shiuly 2023) have shown that carbonate formation can dramatically increase thermal resistance by closing voids and reducing the connectivity of pores. Above a certain concentration of carbonic acid (Samples M4 and M5), either larger pore sizes or structural changes may facilitate gas phase conductivity. This shows the range of carbonic acid (as an optimal one), which gives maximum thermal insulation at structural integrity as well.

The findings are consistent with prior research, including Ta et al. (2023), demonstrating that elevated carbonic acid concentrations may decrease thermal conductivity via mechanisms such as carbonate crystal formation. Carbonic acid interacts with calcium hydroxide, resulting in the formation of calcium carbonate crystals that precipitate within pores, thereby diminishing pore interconnectedness. Calcium carbonate exhibits lower thermal conductivity than air, functioning as a thermal barrier. Furthermore, carbonic acid affects pore structure by creating finer and more uniformly distributed pores, which complicates heat transfer. Concrete exhibiting elevated concentrations of carbonic acid demonstrates decreased capillary absorption, thereby enhancing thermal insulation properties. A comprehensive review by Hore and Shiuly (2023) investigated the relationship between reduced porosity or increased temperature and lower thermal conductivity.

Moreover, Possan et al. (2016) investigated the carbonation process of concrete and its CO₂ uptake during the lifecycle of building structures. The uptake depends on the surface area of concrete exposed to CO₂, which in turn is controlled by the cement type and strength of concrete.

This shows that carbonic acid, as likely present in fluids moving through the cements, would lower thermal conductivity.

RELATIONSHIP BETWEEN THERMAL CONDUCTIVITY AND DENSITY OF LIGHTWEIGHT FOAMED CONCRETE

Figure 6 shows the relationship between density and thermal conductivity for LFCB blocks with different concentrations of carbonic acid cured under standard conditions. The figure demonstrates the relationship between variations in density and alterations in thermal conductivity (Table 4). The findings indicate that the density and thermal conductivity of LFCB blocks increase with elevated carbonic acid concentrations. The specimen M3, possessing a density of 1500 kg/m³, demonstrates the highest thermal conductivity at 2.081 W/m°C. In contrast, specimen M5, which has the lowest density of 1333 kg/m³, shows a thermal conductivity of 1.146 W/m°C.

The trend implies that higher densities can be attained with increased carbonic acid concentrations, reaching an optimum value of 50% carbonic acid, which correlates with enhanced thermal conductivity. The density and thermal conductivity exhibited a decreasing trend upon reaching 75% and 100% carbonic acid concentrations. The increased density minimises voids in the concrete matrix, thus improving the thermal conductivity of the material.

In addition, Figure 7 illustrates the correlation between the thermal conductivity (k) of lightweight foamed concrete under standard curing conditions and its density (ρ). Thermal conductivity is quantified in watts per meter per Kelvin (W/m·K), while density is expressed in kilogrammes per cubic meter (kg/m³). The graph shows a distinct trend indicating that thermal conductivity rises with an increase in concrete density.

The fitted trend line is represented by the equation $k = 0.0166\rho - 7.8937$, indicating a linear relationship between density and thermal conductivity. The R^2 value of the fit is 0.7924, suggesting that roughly 79.24% of the variance in thermal conductivity is accounted for by the variance in density. The elevated R^2 value indicates that density serves as a robust predictor of thermal conductivity for lightweight foamed concrete under the specified curing conditions. It is common for materials with a higher density to have less porosity and a higher thermal conductivity, as shown by the graph, which means that the concrete's capacity to conduct heat grows as its density does.

CONCLUSION

The study documented herein thus investigates the impact of carbonic acid concentration on thermal conductivity

associated with lightweight foamed concrete (LFCB) blocks. It introduces a new approach to enhancing the thermal performance of LFCB via the replacement of water with carbonic acid. The thermal properties of LFCB apparently were influenced, to different degrees, according to the specimen's carbonic acid concentration, with a specific range (50–75%) showing the highest performance in terms of densification and low porosity density. The results add to the evidence that carbonic acid may be an important ingredient in LFCB mix formulations, ones that lead to building materials more sustainable and efficient. Its optimal 50% concentration (M3) showed a thermal conductivity of 2.081 at normal lap curing conditions. Thermal conductivities ranged between 1.038 W/m°C and 2.081 W/m°C for normal curing at 28 days, which results in energy savings for heating or cooling, lower operating cost and a negligible carbon footprint. Additionally, it also presents the effect of carbonic acid levels on the thermal conductivity of LFCB blocks. The study showed that optimum carbonation, which is approximately 50%, has significantly improved the thermal performance of LFCB for potential application in the construction industry as a sustainable building material. These numbers suggest LFCB could provide even bigger reductions in CO₂ emissions if the concrete were used for longer durations under diverse environmental conditions; future research should investigate the durability of LFCB products, retrospective calculations across different environments to isolate cases where additional reductions in CO₂ from alternative approaches might be achievable.

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DECLARATION OF COMPETING INTEREST

None.

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