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Evaluation of Thermal Conductivity of Sustainable Concrete Having Supplementary Cementitious Materials (SCMs) and Recycled Aggregate (RCA) Using Needle Probe Test

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Abstract: The evaluation of thermal properties is commonly conducted to characterize non-structural materials, such as lightweight concrete, that are used for thermal insulation. Such materials are designed for thermal resistivity applications. Due to the increased demand to adopt sustainable practices in the construction industry, municipalities in the United Arab Emirates (UAE) emphasize the use of sustainable materials in construction, such as green concrete. The cement in green concrete is partially replaced with supplementary cementitious materials (SCMs); these materials are by-product waste from other industries. The SCMs can contribute to sustainability by reducing the concrete carbon footprint. They can also help in extending concrete durability and service life. However, there is still a lack in the literature regarding the effects of these materials on the thermal properties of concrete. This paper investigates the thermal properties of sustainable concrete mixes incorporating various types of SCMs. The SCMs that are considered in this investigation are fly ash, ground granulated blast-furnace slag (GGBS), and microsilica. Another way to improve the sustainability of the concrete is to partially replace the natural aggregates with recycled aggregates. Thus, a group of the concrete mixes in this investigation were prepared by replacing 40% of natural aggregates with recycled aggregates to investigate the effects of recycled aggregate on the thermal properties of concrete. Further, the thermal properties of three lightweight concrete mixtures commonly used in construction were evaluated. All concrete mixtures were examined for thermal conductivity and resistivity in accordance with ASTM D5334. The results of this investigation showed that SCMs and recycled aggregates have a significant impact on the thermal properties of concrete. The high replacement of ground granulated blast-furnace slag (GGBS) resulted in a remarkable increase in thermal conductivity. This investigation provides significant conclusions and recommendations that are of practical importance to the construction industry in the UAE to promote sustainability. This research aims at formulating recommendations for the effective use of SCMs in the construction industry in the UAE based on their effects on the thermal properties of concrete.

Keywords: sustainability; thermal conductivity; thermal resistivity; green concrete; supplementary cementitious materials; recycled aggregate concrete; lightweight concrete

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1. Introduction

The intensive industrialization activities in the last decades resulted in tremendous emission of carbon dioxide to the environment that, subsequently, raised awareness and concern about global warming (Koniorczyk and Grymin, 2021). Due to the global growing concern about climate change and the continuous increase in population, there is an increasing demand for energy saving. To overcome this alerting problem, the construction industry in the United Arab Emirates (UAE) is keen to implement sustainable practices. The replacement of Portland cement with cementitious materials (SCMs) has become a common sustainable practice in the UAE construction industry [1]. Currently, the use of

SCMs, in concrete is required in most emirates in UAE, such as Dubai and Abu Dhabi. For example, a circular known as green concrete was developed and adopted in the concrete industry [2]. The proper selection of the SCMs is a key factor in promoting sustainability and enhancing concrete properties. They also reported that SCMs could improve the fresh and mechanical performance of concrete. Literature is rich with data on the impact of those SCMs on the concrete mechanical and durability properties [2–6]. Research performed by Al Shaibani et at. [7] assessed the impacts of different cementitious materials on sustainability and concrete performance in the UAE. It was reported that the incorporation of cementitious materials is a sustainable practice that can reduce CO_2 emissions.

Concrete represents the main element of the interior and exterior envelope of many structures. Thus, it is the first barrier for the thermal transmission of ambient temperature inside/outside buildings [8]. In the UAE, concrete is the main skeleton of most structures, and thus, the used SCMs should not be only evaluated based on their structural performance, but also based on their positive contribution to the non-structural properties of concrete that are related to sustainability. The main non-structural properties to be evaluated are thermal conductivity and resistivity. These properties have recently gained growing concerns in construction [9]. These two properties are important to evaluate the sustainability aspects of concrete that can help in enhancing energy saving. Recently, special attention was paid to evaluate the thermal properties of concrete, to enhance its thermal resistivity and promote energy saving. The thermal properties of concrete were also studied to estimate concrete cracks due to thermal causes [10].

Several research papers studied the effects of concrete constituents on thermal conductivity using different assessment methodologies or testing standards [11,12]. Research conducted elsewhere [13] investigated the impact of pore sizes on thermal conductivity. The investigated concrete mixtures had comparable porosity. It was found that an increase of 0.10 mm in pore size within an aerated concrete mixture resulted in an increase of around 23% in concrete's thermal conductivity and the impact of such an increase on compressive strength was minimal [13]. Another research by Mydin et al. [14] investigated the effect of fly ash on the thermal conductivity of concrete. They reported that a 15% replacement of fly ash, caused a decrease in thermal conductivity by 0.46% compared with a mix with 0% fly ash. However, this effect was reversed when fly ash increased to 30%, where the thermal conductivity of the concrete increased by 3.4% [14]. The thermal conductivity can be also reduced through the proper selection of aggregates with lower thermal conductivity. It was mentioned in ACI 122R-14 that limestone aggregates have relatively low thermal conductivity (1 to 3 W/m °C) [15].

On the other hand, it was found by Du and Ge [16] that external factors can affect the thermal conductivity of concrete mixtures. One of the discussed external impacts was related to the curing duration of the concrete. It was concluded that prolonging the curing duration decreases the thermal conductivity of cement paste and, thus, the concrete. The same investigation characterized the thermal conductivity of internal chemical compounds such as C_3S and C_2S. It was reported that C_3S and C_2S had the following thermal conductivity: 3.35 and 3.45 W/m·K, respectively. Predictive models were proposed to characterize the sustainability of concrete at an early stage of the design of the structures [16].

Knowing that aggregates occupy about 85% of concrete, their characteristics are very important for sustainability. Therefore, current sustainable practice in the UAE construction that focuses mainly on replacing cement with SCMs is not enough, and replacing natural aggregate with recycled aggregates should be also adopted. Hence, replacing aggregates with recycled aggregates is highly beneficial for sustainability. The recycled aggregates used in Abu Dhabi City are usually extracted from construction wastes of demolished buildings in the City. This sustainable approach will reduce the construction wastes that are dumped in landfills, attenuating their harmful impacts on the environment [17]. The freshness, rheology, mechanical properties, and bond strength of recycled aggregate concrete have been addressed and studied elsewhere [18,19]. However, data on the thermal properties of recycled concrete incorporating SCMs are still limited in the literature. Although the thermal properties of the recycled aggregate are linked relatively to the chemical origin of this recycled aggregate or its blend of sources, Smith and Tighe [20] reported that the increase in the replacement of virgin coarse aggregate by recycled coarse aggregate contributed strongly to the reduction of the total thermal expansion coefficient. This was vividly noticeable when the replacement percentages reached 50%. On the other hand, it was found that 15% and 30% replacements of coarse aggregate by recycled coarse aggregate had a minimal impact in reducing the concrete's coefficient of thermal expansion. The concrete mixture containing 50% recycled aggregate showed a thermal expansion coefficient of $4.1 \times 10^{-6}/°C$ in comparison with $5.9 \times 10^{-6}/°C$ for the same with limestone virgin aggregate.

This paper investigates the effects of sustainable materials on the thermal conductivity and resistivity of concrete. The sustainable supplementary cementitious materials (SCMs) that are considered in this investigation are: fly ash, ground granulated blast-furnace slag (GGBS), microsilica, and recycled aggregates. Forty percent of natural aggregates were replaced with recycled aggregates. The SCMs were replaced by a mass of cement. The thermal properties are examined following the standard test method ASTM D5334 [21]. The results are also compared with an alternative test method known as the steady-state thermal transmission test in accordance with ASTM C518 [22]. This was conducted on common structural mixtures. Additionally, three different types of common lightweight concrete mixtures of different dry densities were included in this study. The main goal of this paper is to investigate the influence of SCMs on the thermal properties of concrete prepared with locally available natural and RCA aggregates in the UAE. This research aims at formulating recommendations for the effective use of SCMs in the construction industry in the UAE based on their effects on the thermal properties of concrete.

2. Materials and Methods

The Portland cement used for the entire study was of type 1 and of grade 42.5, conforming with BS EN 197-1 [23]. The used cementitious materials (SCMs) are ground granulated blast-furnace slag (GGBS), fly ash (FA), and microsilica (MS). The cement was replaced with SCMs by mass. GGBS utilized for the experiments is of grade 100 and conforms to BS 6699 standard requirements. Class F fly ash, as per ASTM C618, is used in this investigation. The microsilica used in this study has an activity index of 110% and a silicon dioxide content of 90% and is in accordance with ASTM C1240 standard requirements. Low-range polycarboxylate admixture conforming with type G of ASTM C494 was the superplasticizer used in this study. Locally produced natural aggregates (NCA), recycled aggregates (RCA), and lightweight aggregates were used in this study. The natural aggregates (NCA) used in this investigation were crushed limestone obtained from Ras Al Khaima, United Arab Emirates, with a nominal maximum size of 20 mm and average specific gravity of 2.72. Both natural coarse and fine aggregates conform with BS 882 individual grading limits as well as combined ones. The RCA aggregates are obtained from demolished buildings in Abu Dhabi. The specific gravity of both NCA and RCA aggregates was obtained in accordance with the standard test method of BS 812-2:1995. Two types of lightweight aggregates were used perlite and light-expanded clay aggregate (LECA). Perlite originated from natural volcanic ash that is subjected to rapid cooling and heating, resulting in expanded amorphous particles of alumina silicate. The used perlite has a nominal maximum particle size of 2 mm and complies with ASTM C332 (standard specification for lightweight aggregate for insulating concrete). Perlite aggregate has a specific gravity of 0.20. Perlite consists of perlite ore bubbles and air. The specific gravity of the perlite ore is 2.2, and the air has a specific gravity of approximately 0. Thus, the specific gravity of perlite (combined ore and air) can be estimated, but it cannot be measured, as the bulk density of perlite is 80 kg/m^3, which is much lighter than the oil that is used for specific gravity testing. Hence, perlite floats in oil, so the oil cannot be inserted in the cavities to determine the volume. As the standard test method of BS 812-2:1995 is difficult to be implemented for perlite, a reversed calculation was performed to figure out the specific gravity of perlite. This reversed calculation was performed through the addition of perlite to concrete mixtures of known volume and density as well as having ingredients with known measured specific gravity. Upon the addition of perlite, the new volume and density are measured. Therefore, by knowing the other ingredient's specific gravity and weight, volumetric mix design calculation will be performed given that the air content is separately measured of the same through ASTM C173. As such, the specific gravity of this structure is the theoretical average specific gravity of the perlite ore and of the air.

The light-expanded clay aggregate (LECA) is manufactured by firing clay materials at high temperatures that cause the expansion to the material resulting in porous lightweight clay type of aggregates. The incorporated maximum nominal size of LECA aggregate in this study is 10 mm with a specific gravity of 1.26. This specific gravity was found as per BS 812-2. In accordance with BS EN 13055, the aggregate is considered of lightweight type only if it has a specific gravity of less than 2.0.

Fourteen different concrete mixtures were prepared and cast in 150 mm cube molds to investigate their thermal conductivity and resistivity properties. The samples were divided into three groups, namely, structural normal concrete (SNC), recycled aggregate concrete (RAC), and lightweight concrete (LWC). These groups consisted of six, five, and three mixes for the SNC, RAC, and LWC concretes, respectively. The compressive strengths in the first two mix groups were chosen to match the commonly used grades of 50 and 60 MPa concrete used in practice in the UAE and referred to as C50 and C60. The constituents of the first two groups were chosen to be similar, with the difference of the natural aggregates in the second group being replaced by 40% recycled aggregates. This is with the exception of the "C50 mid GGBS" mix that is present in the first group only. These mixtures were carefully selected based on previous work by the current authors [18,19]. The third group consisted of three lightweight concrete mixes. The concrete resulting from these mixes was identified as lightweight concrete as their measured dry density had a maximum value of 1845 kg/m^3, which is in accordance with the ACI213's definition of lightweight concrete that should have a dry density equal to or less than 1850 kg/m^3. The thermal properties of the three groups were studied, and the results were compared.

It should be noted that the combinations of SCMs in this study were selected based on the common recommendations and practices in the industry in the UAE to ensure mechanical performance, sustainability, and durability. As such, grade 60 concrete mixture for both structural concrete and recycled aggregate concrete groups was achieved by incorporating 50% GGBS and 5% microsilica (commonly used dosage in construction in UAE). Thus, incorporating 5% of microsilica was required to achieve such a high compressive strength of 60 MPa, and to offset the slowing effect of the high dosage of GGBS (50%) for the 28-day strength development.

Similarly, fly ash is usually incorporated in concrete mixtures with conventional grades of below 60 MPa. As the study focuses on the concrete industry interest and the common mixtures being produced, the higher fly ash content in the concrete mixture was avoided due to the effect of fly ash in extending setting time and delaying strength development. Therefore, it is a common practice by the ready-mixed concrete plants in UAE to limit the replacement percentage of Portland cement by fly ash to 35%, which is referred to as a medium replacement. This is despite the fact that international standards permit the incorporation of fly ash at high percentages of up to 55%, such as in CEM IV in accordance with BS EN 197-1:2019 [23] and BS 8500-2:2006 [24].

All the structural and recycled aggregate concrete mixtures were made with total cementitious materials of 420 kg/m^3 and 430 kg/m^3 for C50 and C60, respectively. The free water for structural and recycled aggregate concrete mixtures was maintained at 148 L per m^3. Thus, water-to-cementitious ratios were 0.35 and 0.34 for C50 and C60, respectively. On the other hand, the water-to-cement ratio of the typical lightweight mixtures of foam concrete, perlite concrete, and LECA concrete investigated are 0.45, 0.55, and 0.35, respectively. The absolute volume method (1 m^3) was used to design the concrete mixtures. As such, the total volume of aggregates was kept constant for all mixes. Since the

RCA had less saturated surface particle dry density, the mass of aggregates was modified for each mixture based on the replacement percentage of RCA. The volume of cement paste was also kept constant for all mixes. The saturated surface-dry (SSD) condition was adopted in the mix design for all mixes. It can be noted that the hardened density of structural and recycled aggregate concrete mixtures ranged from 2460 kg/m^3 to 2500 kg/m^3. On the other hand, the hardened density of lightweight mixtures ranged from 1080 kg/m^3 to 1850 kg/m^3.

Table 1 shows the details of the mixtures used in the investigation. It should be noted that, as mentioned earlier, the selected mixes in this study are commonly used by the construction industry in the UAE.

Table 1. Investigated mixtures details for commonly used mixes in UAE construction.

Mixtures Group	Description	Symbol	Grade (MPa)	OPC (%)	GGBS (%)	Flyash (%)	Microsilica (%)	Dry Density (kg/m^3)
Structural Concrete (SC)	C50 low GGBS	SC50G36	50	64	36	-	-	2490
	C50 mid GGBS	SC50G50	50	50	50	-	-	2500
	C60 GGBS + MS	SC60G50M5	60	45	50	-	5	2460
	C50 high GGBS	SC50G65	50	35	65	-	-	2490
	C50 low Flyash	SC50F26	50	74	-	26	-	2470
	C50 mid Flyash	SC50F35	50	65	-	35	-	2470
Recycled Aggregate Concrete (RAC)	C50 low GGBS	RAC50G36	50	64	36	-	-	2460
	C60 GGBS + MS	RAC60G50M5	60	45	50	-	5	2480
	C50 high GGBS	RAC50G65	50	35	65	-	-	2465
	C50 low Flyash	RAC50F26	50	74	-	26	-	2450
	C50 mid Flyash	RAC50F35	50	65	-	35	-	2455
Lightweight Concrete	Foam Concrete	LWFC	1	100	-	-	-	1080
	Perlite Concrete	LWPC	8	100	-	-	-	1340
	LECA Concrete	LWLC	50	67	26	-	7	1845

The fourteen mixtures in this study were subjected to thermal conductivity and resistivity testing in accordance with ASTM D5334-14. The standard is titled "Standard Test Method for Determination of Thermal Conductivity of Soil and Soft Rock by Thermal Needle Probe Procedure". The test was performed on all investigated mixtures' specimens using Thermtest Transient Line Source TLS-50 equipment [21,25], which is a portable thermal conductivity meter for soil, rock, concrete, and polymers, as shown in Figure 1.

(**a**) (**b**)

Figure 1. Thermtest Transient Line Source TLS-50 equipment used to perform thermal conductivity test on concrete cube specimen: (**a**) Thermtest controller unit displaying information. (**b**) Thermtest with connected accessories (serial cable, 50 mm length sensor probe).

Thermtest TLS-50 for concrete has a measurement reproducibility of 2% and accuracy of 5%. It measures thermal conductivity and resistivity in a range of 0.3 to 5.0 W/m·K and 0.2 to 3.3 m·k/W, respectively [25]. Thermtest TLS-50's sensor needle probe is of 50 mm length with 4 mm diameter.

The thermal properties of the thirteen studied mixes were tested on their 150 mm cubes after they were subjected to standard water curing at a temperature of 20 ± 2 °C for 28 days. These tests were performed following the standard test method of ASTM D5334. This test uses a thermal needle probe to evaluate the thermal conductivity of concrete. The tested cubes were first dried for 12 h at room temperature, and then they were followed by sample preparation for testing (Figure 2).

(**a**) (**b**)

Figure 2. Concrete cube samples pre-preparation: (**a**) water curing of the cube samples for 28 days with a maintained temperature of 20 ± 2 °C. (**b**) Concrete drying at room ambient temperature of 20 °C for 12 h.

As an initial step and to prepare the concrete for thermal property testing, 50 mm depth holes were drilled in the top surface of the cube samples. This was performed using a drilling machine with a rotary masonry drill bit of 4 mm. Subsequently, the holes were cleaned from the generated dust during drilling by using compressed air or an air blower. Before inserting the needle probe of the Thermtest inside the hole, thermal grease is used to improve the thermal contact between the probe's sensor and the hardened concrete internal surface. The machine will be turned on upon inserting the needle probe, and the test starts. The Thermtest machine first generates heat, and the temperature readings are recorded at the same intervals. The recorded temperature at the corresponding intervals of heating and cooling through the Thermtest machine's needle probe is concealed automatically within the machine's operating system during the test performance to calculate the thermal conductivity and resistivity of the specimen in-test. The recorded temperature within the test machine was not retrieved as it was not part of the scope of the study. This may be considered as part of a future study in the next further investigation. The needle of the machine has a heating wire and temperature sensor conserved in the 50 mm tube probe that is made of steel. This is the main part of the machine, which is responsible for temperature rise, temperature drop, and the abovementioned measurement over the defined 5 min period of test time.

It should be noted that despite the fact that the cube specimens might be subjected to stacking during the drying process upon the curing, the referred top surface for the 50 mm drilling is one of the remaining 4 or 5 faces of the cubes, which was not stacked in touch with another cube surface. Therefore, and since the hole depth required is only 50 mm, which is one-third of the cube specimen's height and taken in the middle of the surface, any possible deviation in the degree of drying at the far surface will not have an impact on the conductivity measurement reading. Detailed testing procedures are shown in Figure 3.

(**a**) (**b**) (**c**)

Figure 3. Photos for samples preparation and testing using Thermtest TLS-50: (**a**) Cubes' drilling for 50 mm depth using a 4 mm drill bit. (**b**) Filling the thermal compound in the created hole after removing formed dust. (**c**) Inserting the needle probe and testing.

Upon the completion of the heating phase, the cooling-down stage started, and temperature readings were taken at the same intervals [25]. The complete measurement process for one specimen takes about 5 min. Finally, the thermal conductivity is calculated using the following Equation [21]:

$$k = q/4\pi a \quad (1)$$

where k, q, and a are symbols that represent the thermal conductivity in W/m·K, the needle's heating power through a constant current source in W/m, and the slope of temperature growth against the log of time, respectively.

Thermal conductivity indicates how fast heat can flow and transfer through a material. The higher the thermal conductivity, the faster the heat can dissipate through a material. Thermal resistance (R) represents the thermal storage ability of a material. For example, in a passive solar application, the solar panel must be made of conductive materials to maximize the passage of solar heat that will be transferred beyond the surface for more effective heat storage. On the other hand, materials with high thermal resistivity are suitable to be used for thermal storage applications. The thermal properties of concrete depend on the thermal properties of the aggregates, as the aggregate occupies about 75% of the volume of concrete. Many factors have impacts on the thermal properties of concrete, including the type and amount of aggregates, amount of cement paste, air content, and moisture.

Figure 4 shows the results of the Thermtest test for high- and low-conductive materials. The results clearly show the difference between high-conductivity and low-conductivity materials; when the temperature rises, the slope of the linear curve for high-conductive materials is greater than that for low-conductive materials.

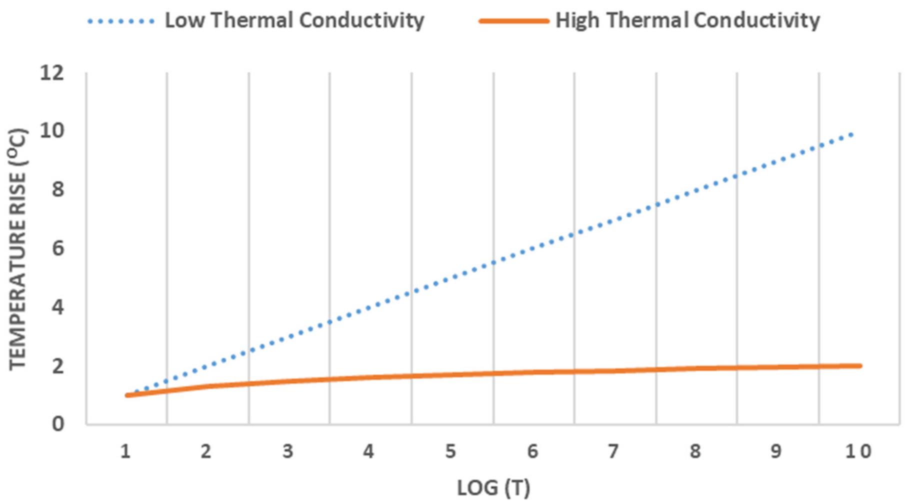


Figure 4. Illustration on Thermtest's calculation for thermal conductivity through the slope of Temperature growth readings versus the logarithm of time relation [25].

3. Results and Discussion

3.1. Thermal Properties of the Studied Structural Concrete Mixes

Figure 5 shows the conductivity and resistivity measurements for the first group of studied mixes, the structural normal-weight concrete mixtures. These mixtures were made with natural concrete aggregates (NCA) and incorporated various blends of SCMs. The conductivity measurements were shown as bar columns and the resistivity as dotted lines. Since the dry hardened density of normal structural concrete mixtures is close to each other (between 2470 and 2500 kg/m^3), their thermal conductivity and resistivity values depended mainly on the incorporated cementitious materials (SCMs). As shown in Figure 5, the higher the replacement of GGBS, the higher the thermal conductivity. It can also be observed that fly ash has a similar effect on conductivity, and the thermal conductivity increased with a higher content of fly ash. This indicates that incorporating SCMs promoted the thermal conductivity of concrete.

Two remarkable increases in thermal conductivity of structural natural aggregate mixtures were recorded due to the increase in the dosage of GGBS. The first increase is when the GGBS increased from 36% to 50%, where the thermal conductivity increased from 0.648 to 1.023 W/m·K (of around 58%). The second increase in conductivity was when cement was replaced with 65% of GGBS. This mix also showed a significant drop in resistivity, and it is referred to in Figure 5 as high GGBS. The results show that this mix has thermal conductivity as high as 2.802 W/m·K. This increase is more than 330% of the conductivity value for the 36% GGBS mixture. In other words, high GGBS replacement caused a more than four times increase in conductivity. When the replacement of cement with GGBS increased from 50% to 65% GGBS (medium to high), the conductivity increased by 175%. Thus, the concrete becomes more thermal conductive at high GGBs content. This is expected, as GGBS is a by-product of the iron industry. This raises concerns related to the sustainability of concrete when high GGBS content is incorporated into concrete. Although replacing cement with 65% GGBS will reduce the contribution of cement to CO_2 emission by 65%, at the same time, the conductivity of concrete will increase remarkably. Thus, more cooling and heating energy may be required for concrete with high GGBS. More emphasis should be put on the insolation procedures for structures built with concrete incorporating high GGBS replacement percentages. Hence, when conducting a full lifecycle assessment of these structures, the CO_2 emission saving generated from the use of less cement in these concrete mixes may be offset by the larger energy losses due to the higher thermal conductivity of these mixes and, in turn, it may result in a less sustainable concrete structure. Since the thermal resistivity in this study is represented using the unit of m·K/W, thus the impact of the thickness of the sample is not accounted for. As can be seen in

Figure 5, the higher the GGBS content, the lower the resistivity. The measured resistivity of the 50% GGBS mixture shows a drop of around 38% in resistivity in comparison with the 36% GGBS mixture. Reported resistivity values by Thermtest TSL-50 are presented in Figure 5. Consequently, the lowest resistivity in this part of the study is 0.356 m·K/W, and it belongs to the high GGBS percentage mixture. This drop is equivalent to 77% relative to the low GGBS mixture's resistivity value.

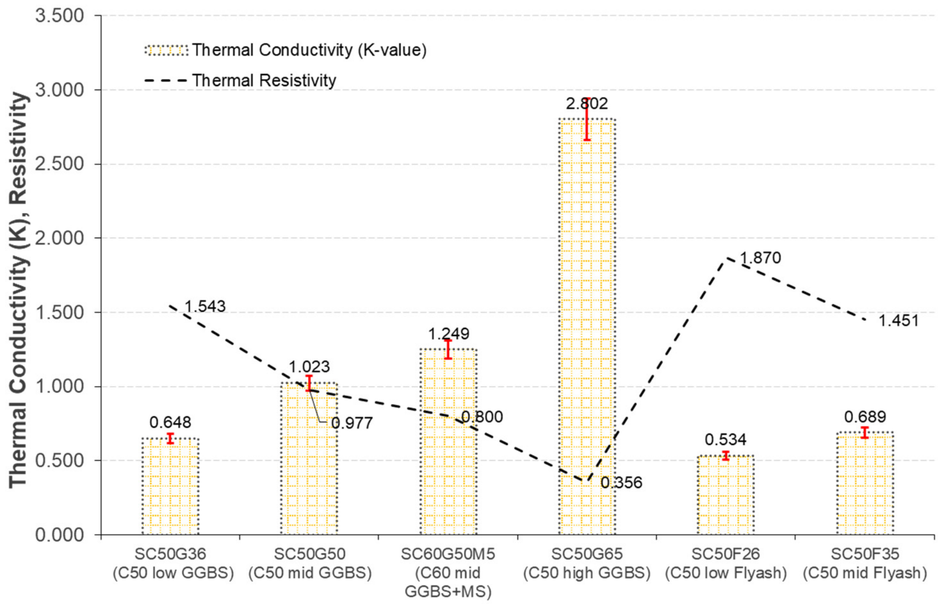
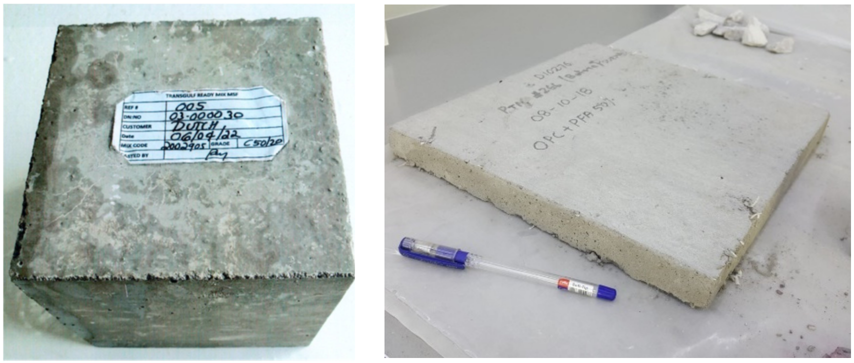


Figure 5. Thermal properties (conductivity in W/m·K, and resistivity in m·K/W) of normal-weight common sustainable structural concrete mixtures.

Incorporating microsilica into the medium GGBS mixture of 1.023 W/m·K shows a slight increase in conductivity (22%) compared to the same mix without MS. The measured thermal conductivity is 1.249 W/m·K (Figure 5). The conductivity of the ternary-blended mixture falls between the medium GGBS and the high GGBS. However, it should be noted that the ternary-blended mixture has a grade of 60 MPa and higher cement content by 10 kg/m^3, and a lower water-to-cement ratio than the rest of the structural mixtures.

Looking into the fly ash mixtures incorporated in the structural investigated concrete mixtures (normal weight and natural aggregate), it can be noted that the increase in thermal conductivity with the increase in fly ash replacement is quite low compared to the case of GGBS. Figure 5 shows that the measured conductivity for low fly ash (26% FA) and medium fly ash content (35% FA) is 0.534 W/m·K and 0.689 W/m·K, respectively. Thereafter, this increase from low to medium fly ash content mixtures is calculated as a 29% increase in comparison with a 58% increase for GGBS. It is worth noting that the low fly ash mixture had the lowest conductivity and, therefore, the highest resistivity (1.870 m·K/W).

The results in this paper of selected mixes using the thermal needle probe method (ASTM D5334-14) were compared with similar mixes measured using the steady-state thermal transmission by the heat flow meter apparatus (ASTM C518-15) that was published in an earlier study by the current authors [8]. The thermal conductivity of structural normal-weight concrete mixes incorporating natural aggregate measured using the method of ASTM D5334-14 was found to be higher than similar mixes measured using ASTM C518-15 that was previously reported in a published work by the current authors [8]. For example, the thermal conductivity of the conventional sustainable structural concrete incorporating 60% GGBS measured using the method of ASTM C518-15 was 0.423 W/m·K [9]. That mix had a grade of 50 MPa and a dry density of 2450 kg/m^3. It should be noted that the mix had GGBS content between the C50 mid GGBS (50 GGBS) and C50 high GGBS ((65 GGBS)) for the mixes in the current study. Thus, its thermal behavior can be comparable to both SC50G50 and SC50G65 mixtures. The thermal conductivities of SC50G50 and SC50G65 are 1.023 and 2.802. Thus, the method used in this study (ASTM D5334-14) gives measurement more than three times the method of ASTM C518-15. This difference in the results between the two methods is related to the type of methodology used to evaluate thermal conductivity following different standards, as each of them uses different testing factors, such as the sample's geometry, preparation procedures, and heat transmission assessment (see Figure 6). The system used in this study does not account for the thickness of the study. The system herein is more accurate than the ASTM C518-15 system in revealing the thermal properties of a material. The ASTM C518-15 measures the thermal transmission properties through specific types of material having certain designed thicknesses. Therefore, it should clearly mention the method that was used when reporting the thermal properties of concrete material. It is recommended to conduct a further comprehensive experimental program considering more types of materials and combinations in order to propose a relationship between the two methods, so a correlation between the results from the two testing methods can be developed.



(**a**) (**b**)

Figure 6. Specimens' geometry for thermal testing: (**a**) cube concrete specimen with a dimension of 150 × 150 × 150 mm for testing in accordance with ASTM D5334-14 and (**b**) plate concrete specimen with a dimension of 40 × 300 × 300 mm for testing in accordance with ASTM C518-15.

3.2. Thermal Properties of the Studied Recycled Aggregate Concrete Mixes

Similar to the normal structural concrete mixtures with natural aggregate, the hardened densities of recycled aggregate concrete mixtures were close to each other and ranged from 2450 to 2480 kg/m^3. Figure 7 shows the results of the thermal conductivity and resistivity of recycled concrete mixtures investigated. The effects of SCMs on the thermal properties of RCA concrete seem to be similar to their effects on the normal structural concrete mixtures; the more the SCMs replacement, the more the thermal conductivity and the lower the resistivity. When the GGBS content increased from 36% (for RAC50G36) to 65% (for RAC50G65), the thermal conductivity increased from 0.648 to 2.802 W/m·K, and the resistivity decreased from 1.543 to 0.356 m·K/W. It should be noted that the rate of the increase in conductivity is 4.3, and the rate of the decrease in resistivity is almost the same at 4.3 (Figure 7).

On the other hand, the ternary blend recycled aggregate concrete mixture (C60 GGBS + MS) that incorporated 50% GGBS and 5% microsilica exhibited the lowest thermal conductivity (0.580 W/m·K) and, consequently, the highest resistivity (1.724 m·K/W) among the other investigated recycled aggregate concrete mixtures.

Unlike the marginal impact of fly ash content on the thermal properties of normal structural concrete mixtures with natural aggregates, the effect of fly ash on the thermal properties of RCA concrete was significant. For example, the measured conductivity of medium fly ash content mixture (C50 mid fly ash) was 2.780 W/m·K, while it was 1.05 W/m·K for low fly ash content mixture (C50 low fly ash). This conductivity value is also very close to the values for high GGBS mixtures. The thermal resistivity decreased from 0.949 to 0.360 m·K/W. This is likely due to the higher porosity of recycled aggregate concrete compared to normal aggregate concrete, where the fly ash will fill the porosity existing in the RAC by its physical filling and pozzolanic reaction, which densifies the RAC.

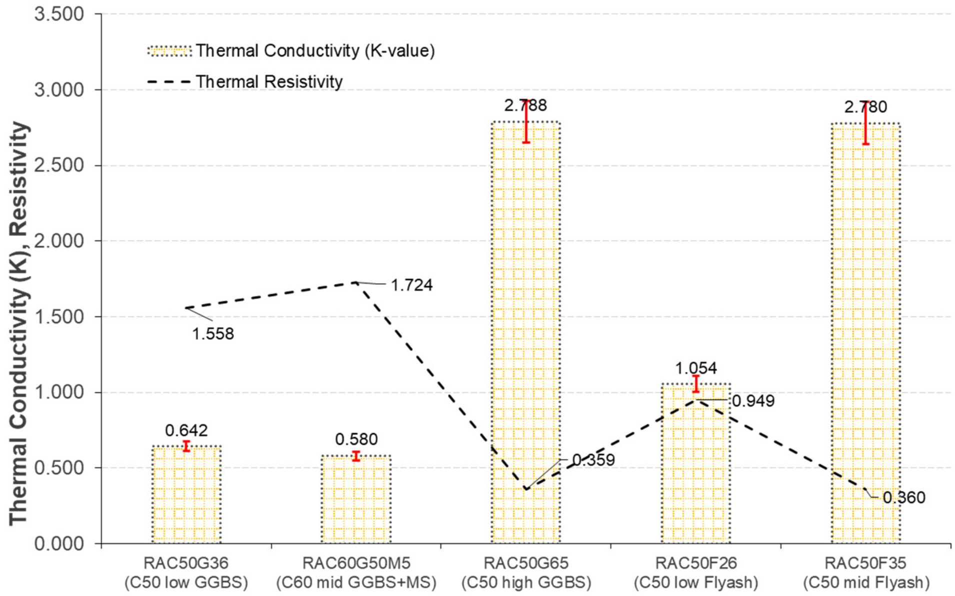


Figure 7. Thermal properties (conductivity in W/m·K, and resistivity in m·K/W) of recycled aggregate structural concrete mixtures.

Figure 8 compares the thermal properties of recycled aggregate concrete mixtures with equivalent mixes made with natural aggregates, denoted in this investigation as structural concrete mixtures. As shown in the figure, both RCA and NCA mixes incorporating GGBS had comparable thermal conductivity for low and high GGBS contents. For example, the thermal conductivity of RAC with low GGBS was 0.642, and it was 0.648 for NAC for a similar mix. The thermal conductivity of binary blends with high GGBS (65%) for RAC and NAC were comparable with just a 0.5% difference. On the other hand, the results for thermal resistivity for RAC and NAC incorporating GGBS are very close to each other, with a percentage difference of less than 1% (Figure 8). This indicates that incorporating GGBS has neutralized the effect of RCA on the thermal properties of concrete. Thus, the replacement of NCA with 40% RCA showed a marginal impact on thermal properties when GGBS was incorporated, as the concrete experienced just a 1% difference in thermal conductivity and resistivity between NAC and RAC.

However, the ternary blend mixture (50% GGBS and 5% microsilica) of grade 60 had reverse thermal properties than the mixtures with GGBS, as the mixture with RCA had lower thermal conductivity than the mixture with NCA. The thermal conductivity of RAC was 0.580 W/m·K, while that of NAC was 1.249 W/m·K. Thus, the ternary blend RAC mix had about 54% lower thermal conductivity than the ternary blend NAC mix. On the other hand, the thermal resistivity was higher for RAC compared with the NAC mix (see Figure 8).

Nevertheless, the incorporation of fly ash in concrete had a noticeable impact on thermal properties. The more the content of fly ash, the higher the thermal conductivity and the lower the thermal resistivity. However, the fly ash has a higher impact on the thermal properties of RAC than the NAC. When the fly ash content increased from 26% to 35%, the thermal conductivity for RAC increased by 2.6 times, while it increased only by 1.3 times for NAC (see Figure 8). Similarly, the resistivity for RAC decreased by 2.6 times when fly ash content increased and by 1.3 times for NAC. Further, the impact of fly ash on thermal properties is higher for RAC compared with NAC. The structural concrete mixtures containing fly ash displayed a remarkable increase in thermal conductivity and a noticeable decrease in thermal resistivity when 40% recycled aggregate was introduced. The thermal conductivity for RAC with mid fly ash was four times higher than the corresponding mix with NCA. For a low fly ash content mix, the thermal conductivity for NAC was two times higher than for the NAC. This indicates that the higher content of fly ash, the more the difference between the thermal properties between RAC and NAC (see Figure 8). It should be noted that this experimental investigation should be extended in future work to consider concrete mixes with higher replacement levels of RCA (up to 100%) to further study the effects of SCMs on the thermal properties of RCA concrete.

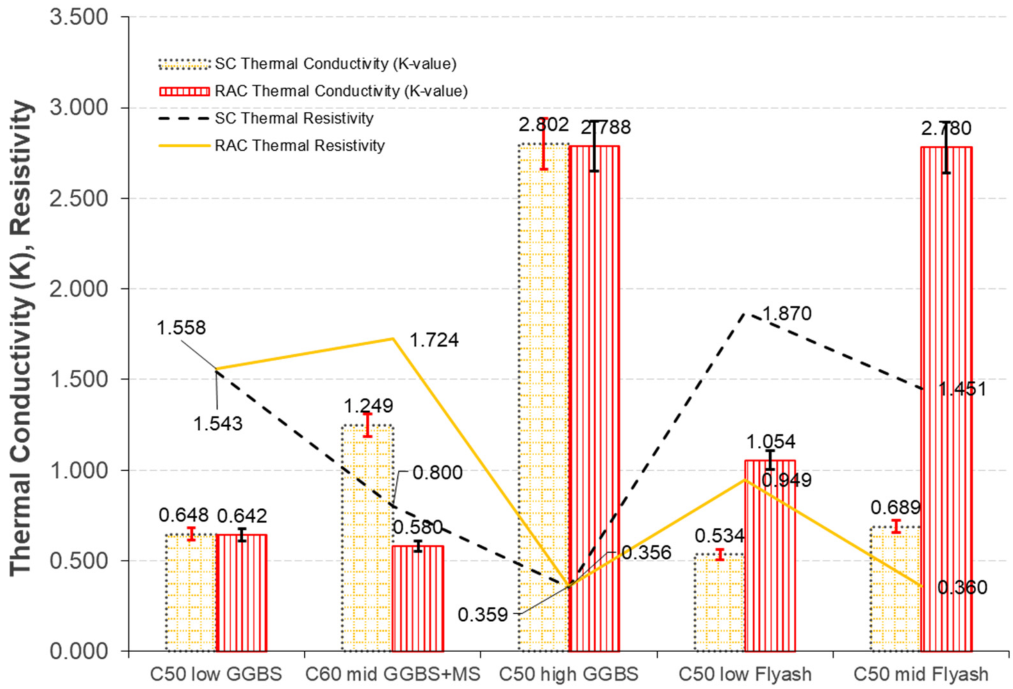


Figure 8. Impact of incorporating recycled aggregate (RAC) on thermal properties (conductivity in W/m·K, and resistivity in m·K/W) of structural concrete (SC) mixtures.

3.3. Thermal Properties of the Studied Lightweight Concrete Mixes

Figure 9 shows the thermal properties of lightweight concrete measured using Thermtest TLS-50. The thermal conductivity values were displayed using bar columns, and the thermal resistivity results were shown as a dotted line. It should be noted that a larger scale was used in Figure 9 as the magnitude of thermal resistivity of foam concrete exceeded 3000 m·K/W, unlike in the case of SC and RAC, where the values of thermal resistivity were lower than 3000 m·K/W. As expected, the thermal conductivity of the lightweight mixes was much lower than that for the other two groups, i.e., the structural normal concrete and the RCA concrete. The conductivity values for foam concrete and perlite concrete were 0.318 W/m·K and 0.371 W/m·K, respectively. The highest resistivity in this investigation was recorded for the foam concrete (3.143 m·K/W), followed by the perlite concrete (2.695 m·K/W).

The thermal conductivity of the structural lightweight mixture with LECA aggregate is more than two times the thermal conductivity of the other two lightweight mixtures. The thermal conductivity of the LECA concrete mix was 0.613 W/m·K, which is close to the recorded thermal conductivity of the conventional structural concrete, specifically with SC50G36, RAC50G36, and SC60G50M5 mixtures, despite that the LECA concrete has a lower density (1845 kg/m^3) than the conventional structural concrete (2450).

Figure 9 also shows the density of the three lightweight mixes. It can be noticed that when the density is higher, the conductivity is also higher. This is reasonable since when the concrete is denser will have less air content and more solids in its structure. Air is known as a thermal insulator material. The densities of the lightweight mixes are 1080, 1340, and 1845 for LWFC, LWPC, and LFCA, respectively, and the conductivities of these mixes are 0.318, 0.371, and 0.613, respectively.

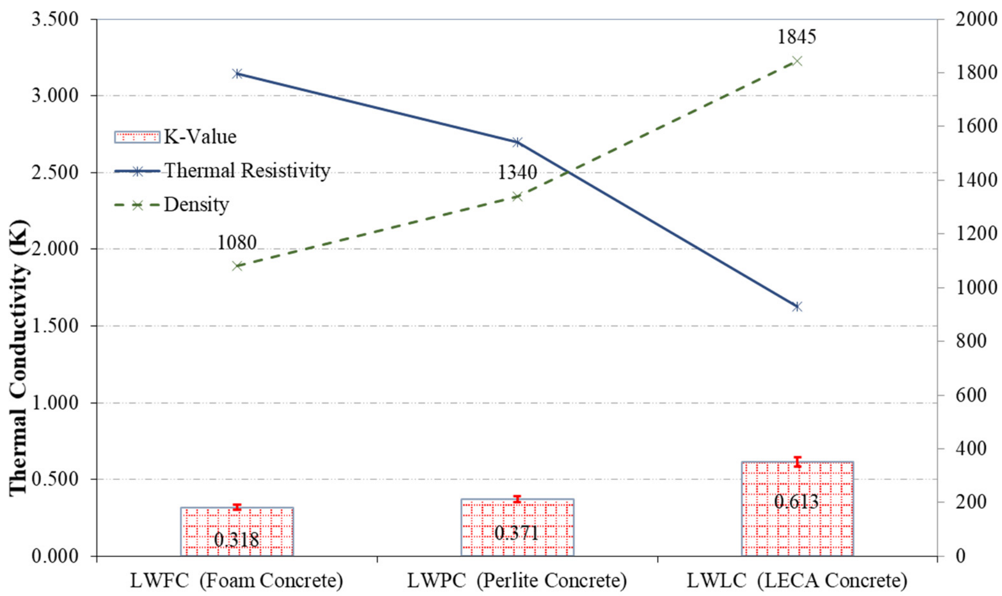


Figure 9. Thermal properties (conductivity in W/m·K, and resistivity in m·K/W) and dry density of investigated lightweight concrete mixtures.

The relationship between the lightweight concrete mixes and their corresponding measured dry density was investigated, as these mixes had different densities. On the other hand, the densities of structural concrete mixtures were close (2450–2500 kg/m^3). The thermal conductivity of the three lightweight mixes was plotted against the corresponding density in Figure 10. It is clear that there is a suitable relationship between the conductivity and concrete density, as the data points were best fitted to linear function with high R^2 = 0.97.

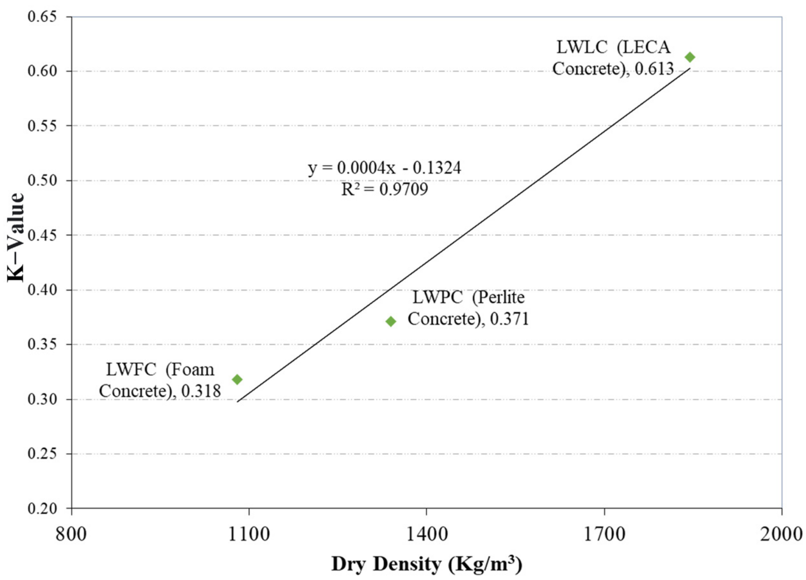


Figure 10. Linear regression between thermal conductivity in W/m·K and dry density of the lightweight group's mixtures.

3.4. Discussion

It should be noted that the densities of the structural concrete and RCA concrete mixtures were comparable, and thus the density of these mixes does not play a key factor in the variations of measured thermal properties. The measured increase in thermal conductivity with the increase in GGBS or fly ash content in the concrete can be related to the pozzolanic effect, as further calcium-silicate hydrate (CSH) is generated in the cement paste. This takes place in the second stage reaction between SCM and the hydration component of calcium hydroxide (CH). This further reduces the concrete porosity making its structure denser through more particle contact and homogeneous distribution [26]. The reduction in porosity can be related to the increase noted in the thermal conductivity with the increase in SCM.

On the other hand, it was found by Choktaweekarn and Tangtermsirikul [27] that incorporating fly ash at high replacement percentages may reduce the thermal conductivity of the concrete at an early age, especially within the first 7 days, but yet it continues to increase with the increase in age as a result of the abovementioned reaction that later offset the reduction of thermal conductivity related to fly ash material. Therefore, the thermal properties of concrete are time dependent, as the pozzolanic reaction continues for the later age of concrete curing, which is 28 days. Further, the used fly ash was of high Blaine with corresponding retained on the 45-micron sieve as low as 9%. This created a better physical filler and higher pozzolanic reactivity at a later age and, in the long term, can densify the matrix of the resulting CSH and lower the porosity. Those factors combined caused opposing effects on the expected reduction of the thermal conductivity when fly ash is introduced to the concrete mixture.

The coefficient of thermal expansion of several concrete ingredients was reported by Choktaweekarn and Tangtermsirikul [27]. For example, the thermal expansion of cement, fly ash, and limestone, are 14.4×10^{-6}, 6.45×10^{-6}, and 4.5×10^{-6}, respectively. Although the coefficient of thermal expansion of concrete can be initially estimated by summation of the volumetrically weighted average of the thermal expansion of its ingredients, the effect of the degree of cement hydrations and pozzolanic reactions of SCMs have significant impacts on this measurement [27]. For example, although fly ash has a relatively lower thermal expansion coefficient than other concrete ingredients, the results in the current study showed an increase in the thermal expansion of concrete with a higher replacement level of fly ash. Knowing that the measurement was taken at 28 days of curing, the pozzolanic reaction was able to offset the lower expansion of the fly ash by densifying the concrete structure. Further, the used fly ash has a high specific surface of 800 m^2/kg, which is also another factor attributed to the increase in thermal expansion of fly ash concrete through densifying its structure.

4. Conclusions

The paper studied the thermal properties of various types of structural and non-structural concrete mixtures. The effects of sustainable cementitious materials and recycled aggregates on thermal properties were investigated. The thermal properties were measured using Thermtest TLS-50's sensor needle probe according to the standard test method referred to as ASTM D5334. The results of selected mixes using Thermtest TLS-50's (ASTM D5334) were compared with similar mixes measured using the steady-state thermal transmission by the heat flow meter apparatus (ASTM C518-15). The paper aimed to investigate the influence of SCMs on the thermal properties of concrete prepared with locally available natural and RCA aggregates in the UAE. This research aims at. The ultimate goal of the paper is to formulate recommendations for the effective use of SCMs in the construction industry in the UAE based on their effects on the thermal properties of concrete in order to promote sustainability by characterizing concrete according to its thermal properties. The following conclusions can be drawn from this investigation:

1. As a general finding, increasing SCM (GGBS and Flyash) content in the concrete mixture increased its thermal conductivity.

2. GGBS showed a high impact on thermal properties, as the thermal conductivity increased four times when the dosage increased from low to high.
3. Sustainability should be checked when GGBS is used at high dosages. GGBS was found to have a high thermal conductivity, which may produce structures with higher energy dissipation than those produced using concrete incorporating lower dosages or no GGBS replacement. When conducting a full lifecycle assessment of the structure, the CO_2 emission saving generated from the use of less cement in the concrete mix may be offset by the larger energy losses due to the higher thermal conductivity of the concrete incorporating high dosages of GGBS.
4. Due to the different heat transmission methodologies and different sample geometry and preparation, the reported thermal conductivity value in accordance with ASTM D5334-14 is found to be higher by 3 to 6 times than the values reported using steady-state thermal transmission by the heat flow meter apparatus in accordance with ASTM C518-15.
5. The ternary-blended mixture (50% GGBS and 5% of microsilica) with 40% recycled aggregate had the second lowest thermal conductivity among the structural mixtures.
6. Substituting 40% of natural aggregates with recycled aggregates has negligible impact on the thermal properties of concrete incorporating GGBS, as the concrete experienced just a 1% difference in thermal conductivity and resistivity between NAC and RAC.
7. Fly ash showed more impact on RAC compared with NAC, as the thermal conductivity of RAC increased by 2.6 times when fly ash content increased from 26% to 35%, while the increase was only 1.3% for NAC.
8. The conductivity measurements for lightweight foam concrete and perlite concrete reported the lowest thermal conductivity results.
9. LECA concrete expressed a relatively high thermal conductivity as a lightweight concrete mixture, which is very close to the normal-weight structural concrete mixtures despite its lower dry density of 1845 kg/m^3.
10. Sustainability considerations in construction should not be only based on one factor related to the cement contribution of CO_2, but other factors, such as the effects of the SCMs on the thermal properties of concrete, should also be accounted for.

5. Future Study and Recommendations

It is recommended to further investigate the relationship between different combinations of fly ash and various recycled aggregate percentages to reach a more comprehensive conclusion on the influences of these materials on the thermal properties of concrete. Further investigation is recommended to study the development of the thermal expansion of concrete at various curing ages up to 180 days, considering the coefficient of thermal expansions of each of the concrete ingredients. In this recommended study, microstructure photographs of mixed materials will be taken.

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