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Assessment of thermo-mechanical performance of lightweight fibre-reinforced LECA concrete for enhanced energy efficiency

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A R T I C L E I N F O

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A B S T R A C T

This study investigates the thermo-mechanical behaviours of lightweight fibre-reinforced LECA concrete. The correlation between fibre composition, porosity and temperature has been analysed, leading to the development of prediction models for each thermal property. The models effectively capture the variability of the heterogeneous concrete, exhibiting R^2 values > 0.98. The findings reveal superior mechanical performance in concrete containing 1–1.5 % steel fibre (STF). Furthermore, nonlinear fluctuations resulting from variations in thermal pathways are observed with intermittent changes in thermal properties, particularly when STF >0.5 %. In all cases examined, the STF concrete consistently exhibits higher thermal and mechanical properties compared to hybrid STF + PPF concrete. While the intricate interplay between STF and the concrete matrix renders it ideal for tailored applications, the stable thermal response of the hybrid fibre concrete showcases beneficial performance in thermal efficiency, characterised by lower thermal conductivity and diffusivity relative to STF concrete. Nonetheless, the optimal performances, based on the combined thermo-mechanical responses, were identified in concrete with the least porosity at 0.5 %STF and 0.75 %STF +0.2 %PPF, yielding an increase of 8.7 % and 4.2 % in compressive and tensile strength, respectively, compared to the plain concrete. Furthermore, the hybrid fibre concrete shows a 5 % reduction in thermal conductivity and diffusivity relative to STF concrete, coupled with increased specific heat and thermal effusivity at elevated temperatures in both concrete, signifying the exceptional energy performance efficiency of LECA concrete across varying temperatures.

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1. Introduction

The construction industry is constantly evolving, driven by the demand for sustainable, durable, and cost-effective building materials. One innovative material gaining attention is lightweight fibre-reinforced LECA concrete (LFRLC), which offers a unique blend of reduced weight and enhanced mechanical properties. Other notable lightweight aggregates include Coke breeze [1], vermiculite [2], pumice and perlite [3]. Research has generally shown that lightweight concrete exhibits improved thermal properties [4–7] which can vary depending on the density and porosity of the lightweight aggregate used [5,7,8].

Previous studies have examined the behaviours of LECA concrete under various scenarios. Notably, the structural performance of polypropylene fibre (PPF) LECA concrete has been extensively investigated [9] revealing a significant improvement in impact energy absorption, crack resistance and a 55.4 % improvement in residual strength with the addition of 1 %PPF. Additionally, Murugan et al. [8] explored the influence of partially replacing LECA on the overall mechanical properties of concrete and identified 10 % as optimal. However, Zakaria et al. [10] reported a general decline in mechanical properties with an increase in LECA content, but with consequent improvement in thermal conductivity which is due to increased porosity and water absorption.

Over the years, there have been growing efforts to understand the thermal behaviour of lightweight concrete to enhance energy efficiency, reduce energy consumption, and encourage green and sustainable construction. To achieve energy efficiency in accordance with SDG 7, it is essential to significantly reduce reliance on conventional fossil fuels, thereby minimizing CO_2 emissions. In pursuit of this objective, researchers have explored the thermal behaviour of lightweight concrete materials, investigating both lightweight and their potential for efficient energy performance. The use of thermal mass materials, such as concrete, has been acknowledged as an efficient strategy to curb energy consumption in structures [11]. Although conventional concrete made with natural aggregate is known for its superior mechanical properties, it typically exhibits poor thermal performance. Research has shown that concrete reinforced with STF exhibits high thermal conductivity, while LECA concrete demonstrates superior thermal properties at 0.35 % polypropylene fibre, outperforming STF in this regard [7]. Also, Yong et al., [6] found that incorporating polypropylene fibres into lightweight foamed concrete can significantly lower thermal conductivity and enhance thermal insulation by up to 16.3 %, attributed to the disruption of heat flow within the concrete. Investigations involving Sisal [12] and Sugarcane fibres [13] also indicate an improvement in the thermal properties of lightweight foamed concrete. The study reported a reduced thermal conductivity of 0.1543W/(mK), along with increased diffusivity and decreased specific heat at an optimal 0.45 % fibre content. Similarly, an optimal fibre content of 0.45 % was reported to have yielded the best thermal properties. While FRCs offer potential benefits for improved thermal properties, it is important to acknowledge potential trade-offs, as various factors such as fibre type and content can distinctly influence the thermal properties of concrete [14,15].

Moreso, lightweight fibre-reinforced concrete exhibits unique thermal behaviours that are influenced by temperature variations. The incorporation of different fibre types influences the thermal properties of concrete, which are important for applications in environments with fluctuating temperatures, as these properties determine the material insulation capabilities and structural integrity under stress. In this context, some behaviours of different fibre-reinforced concrete under increasing temperatures have been studied. For instance, a study found a linear decrease in thermal conductivity and diffusivity with increasing temperature [16]. Another study noted that polypropylene fibre-reinforced concrete experienced increased porosity and cracking due to fibre evaporation at high temperatures, leading to reduced thermal conductivity [14]. In addition, lightweight concrete produced with volcanic pumice and fibres demonstrated superior mechanical properties after exposure to high temperatures, indicating commendable thermal resilience [17].

Although the thermal performance of lightweight concrete has been explored for efficient energy performance, to the best of the authors' knowledge, the thermal properties of LECA concrete reinforced with hybrid steel and polypropylene have not yet been elaborately investigated. Thus, this study aims to present a comparative analysis of the thermo-mechanical properties of LECA concretes produced with steel as well as hybrid steel and polypropylene fibre. In pursuit of an efficient and sustainable material with a reduced carbon footprint, 13 % of the cement was replaced with Ground granulated blast furnace slag (GGBFS), while the natural aggregate was completely replaced with LECA. The GGBFS is recognised for its ability to improve the workability, strength and durability of concrete while reducing its carbon footprint. Thus, the synergy between the concrete matrix and GGBFS offers an opportunity to create a composite material that leverages the advantages of both components. The study explored various properties such as microstructural properties, porosity, water absorptions, compressive, and split tensile strength have been investigated with varying fibre content. The thermal properties were assessed using the Fox50 series Steady-State Heat Flow Meter, with analyses conducted for each concrete mix considering fibre volume fractions, porosity, and temperature.

The significance of this study lies in its potential to deepen the understanding of the thermo-mechanical performance of fibre-reinforced LECA concrete. Notably, it explores and presents a comparative analysis of the behaviour of steel versus hybrid steel and polypropylene fibre in LECA concrete, taking into account the porosity, fibre content, and temperature (0 °C −50 °C). Additionally, the inclusion of GGBFS promotes environmental sustainability by lowering the carbon footprint associated with concrete production. The overall findings aim to provide valuable insights that will serve as guidance for the development of more efficient and sustainable lightweight construction materials.

2. Experimental procedures

2.1. Material details

This section provides details of the material used in the study. For easier reference, materials are grouped based on functions.

2.1.1. Binders

Throughout this study, a grade 42.5 cement conforming to ASTM Type 1 was used. In addition, Ground Granulated Blast Furnace Slag (GGBFS) equivalent to 13 % by weight of cement was incorporated into the concrete mix for improved durability and to ensure sustainability and reduced carbon footprint in accordance with SDGs 12 and 13. The cement has a specific gravity of 3.13 and a surface area of 3509 cm^2/g, while the GGBFS has 2.9 specific gravity with a fineness of 4050 cm^2/g. The oxide compositions of both binders are provided in Table 1.

2.1.2. Aggregate

Lightweight Expanded Clay Aggregate (LECA) was completely used instead of the natural aggregate to actualise the lightweight of the resulting concrete, while the fine sand was sourced from local mines. The LECA has a 780 kg/m^3 bulk density and 1.52 specific gravity, while the size ranges between 4 and 15 mm. On the other hand, the fine sand sizes are below 4.75 mm, with specific gravity and fineness modulus of 2.68 and 2.60 respectively.

2.1.3. Fibres

Two types of fibres are used, namely hooked-end steel fibre (STF) of 35 mm length and polypropylene fibre (PPF) of 19 mm length. The choice of lengths is based on the reported influence of fibre length on the mechanical properties of LECA concrete [9,18]. The physical properties of STF and PPF are provided in Table 2. In addition, Fig. 1 illustrates the fibres and other materials used to produce concrete.

2.1.4. Plasticiser

A dosage of superplasticiser ranging from 1.0 % by weight of cement was used, conforming with BS 934-2.

2.2. Concrete mix

To assess the influence of different fibre types on the mechanical and thermal properties of the LECA concrete, various concrete mixes, as shown in Table 3, were prepared for SFT, PPF and STF + PPF, which were compared normal-weight concrete (NWC), and non-fibre reinforced LECA concrete (LWAC).

Prior to each mix, a measured quantity of LECA is immersed and soaked in clean water for 30 min in a steel container with the lid tightly positioned to ensure all LECA are submerged. Thereafter, the aggregate is surface-dried using a towel. The aim was to ensure no the aggregate is devoid of free surface water while maintaining saturated internal voids.

2.3. Testing methodology

2.3.1. Sample preparation

The thermal properties were tested for each concrete mix using specimens that had cured for 60 days. The tested properties, including thermal conductivity, specific heat, thermal effusivity, and thermal diffusivity were measured using a Fox50 series Heat Flow Meter, in accordance with ASTM C518-98 [19] and ASTM C1784-20 [20]. The Fox50 is an industry-based steady-state heat flow meter designed for direct measurement of thermal conductivity in low to medium-conductivity materials within a temperature range of 20 °C and 300 °C. It features high-performance, proprietary thin film heat flux transducers, digital thickness measurements, and a responsive temperature control integrated contact-resistance correction.

The disc specimens were cut to varying thicknesses ranging from 10 mm to 20 mm as shown in Fig. 2. These discs were derived from cylindrical core specimens measuring 55 mm in diameter and 150 mm in length, which were extracted from 150 mm concrete cubes that had been cured in fresh tap water for 60 days. For each concrete mix, three discs were prepared, each set for 10 mm and 20 mm.

Table 1
Chemical oxide composition of binders used.

Oxide Composition (%)	Cement	GGBFS
CaO	63.39	49.75
SiO_2	19.80	29.34
Al_2O_3	5.09	11.73
MgO	2.49	4.19
Fe_2O_3	3.10	0.53
K_2O	0.59	0.45
SO_3	2.40	2.08
Na_2O	0.18	0.00

Table 2
Properties of steel and polypropylene fibres.

Properties/fibre types	Steel fibre	Polypropylene fibre
Shape of fibre	Hooked-end	Straight
Length (mm)	35	19
Diameter (mm)	0.35	0.022
Aspect ratio (l/d)	100	864
Density (kg/m^3)	7.8	0.91
Tensile strength (N/mm^2)	1050	350

Fig. 1. (a) LECA (b) GGBFS (c) hooked end steel fibre (d) Polypropylene Fibre.

Table 3
Concrete mix.

Mix Code	Binders (kg/m^3)		Aggregate (kg/m^3)		Fibre (%)	w/c
	Cement	GGBFS	LECA	Fine sand		
NWC	400	60	904	822	0.00	0.35
LWAC-0 %	400	60	506	837	0.00	0.35
STF-0.25 %	400	60	506	837	0.25	0.35
STF-0.50 %	400	60	506	837	0.50	0.35
STF-0.75 %	400	60	506	837	0.75	0.35
STF-1.0 %	400	60	506	837	1.00	0.35
STF-1.5 %	400	60	506	837	1.50	0.35
PPF-0.1 %	400	60	506	837	0.1	0.35
PPF-0.2 %	400	60	506	837	0.2	0.35
PPF-0.3 %	400	60	506	837	0.3	0.35
STF0.5 % + PPF0.2 %	400	60	506	837	0.5,0.2	0.35
STF0.75 % + PPF0.2 %	400	60	506	837	0.75,0.2	0.35
STF1.0 % + PPF0.2 %	400	60	506	837	1.0,0.2	0.35

The disks were oven-dried for 24 h and subsequently placed in a desiccator at room temperature (28^{o}c) before being tested using a heat flow meter.

2.3.2. Experimental tests

Table 4 provides a summary of the tests conducted, detailing the specimen sizes and reference standards. The assessments included workability, water absorption, porosity, dry density, as well as compressive, split tensile strength and thermal properties. The thermal properties encompassed thermal conductivity, specific heat, effusivity and diffusivity. The workability of each concrete mix was assessed using a slump test. Compressive and split tensile strength were tested using a universal testing machine available at the civil engineering laboratory of National Energy University, Malaysia. The water absorption properties were determined following the guidelines outlined in ASTM C642 [21], and accordingly, the water -to- (Cement + GGBFS) ratio was adjusted.

3. Microstructural analysis of the fiber reinforced LECA concrete

The microstructural analysis of the LECA concrete was conducted on three concrete variants produced without fibre (LWLC), with only steel fibre (STF), and with a hybrid steel + polypropylene fibre (STF + PPF). For this analysis, the FEI Quanta 400 high-resolution field emission scanning electron microscope was employed, as shown in Fig. 3. The equipment can achieve a maximum magnification capability of over 100,000x, making it a versatile tool for high-resolution imaging across various applications. The objective is to examine, through the scanning electron microscope (SEM) micrographs, the interfacial zones (ITZ) between the LECA, STF and hybrid STF + PPF and to assess their influences on the mechanical properties of the proposed concrete formulations. A representative sample from each concrete mix, reflecting the area of interest, was carefully cut from tested specimens using minimal force to minimize microstructural damage. The samples were then dried in a desiccator to eliminate moisture without causing shrinkage or cracking.

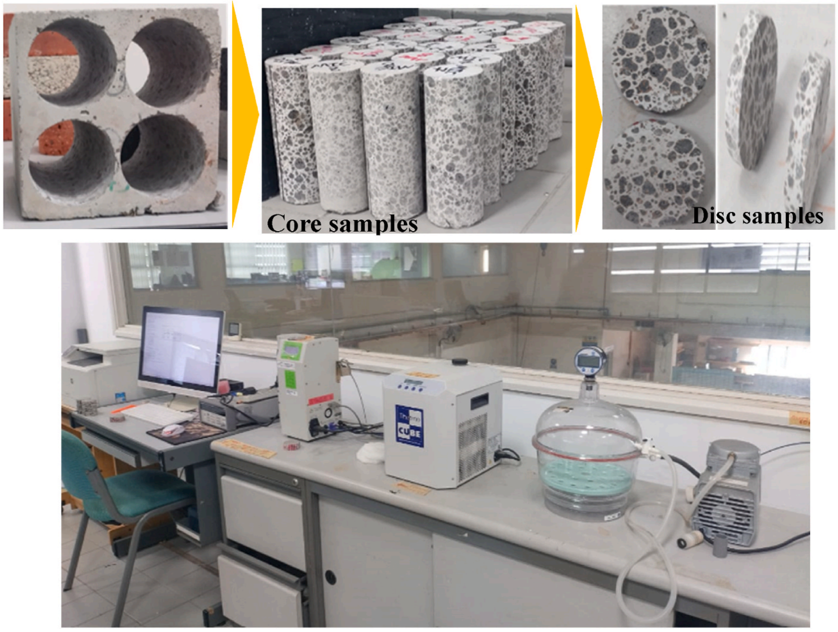

Fig. 2. Experimental Setup for thermal properties using FOX50 Heat Flow Metre.

Table 4
Summary of test carried out.

Test	Specimen size	Curing age	Reference Code
Workability	NA	NA	ASTM C143 [22]
Water absorption	100 mm square cube	Not Applicable	ASTM C642 [21]
Porosity	100 mm square cube	28days	ASTM C642 [21]
Dry density	100 mm square cube	28 days	ASTM C642 [21]
Compressive test	100 mm square cube	7 and 28 days	BS EN 12390 - 4 [23]
Spit tensile test	100 × 200 mm cylinder	28 days	BS EN 12390 - 6 [24]
Thermal conductivity	Concrete disc: 150 mm diameter, 10 mm thickness	60 days	ASTM C518-98 [19]
Specific heat			ASTM C1784-13 [20]
Thermal effusivity			ASTM C518-98 [20]
Thermal diffusivity			ASTM C518-98 [19]

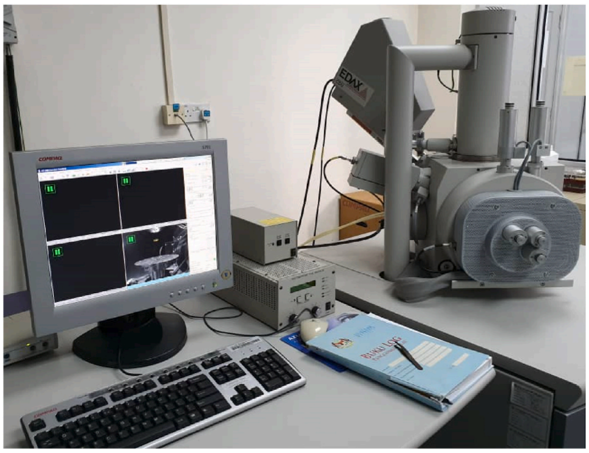

Fig. 3. SEM experimental setup using FEI Quanta 400.

Once dried, the specimens were secured onto the SEM stub, and a clean brush was used to remove any loose particles before placing the sample in the SEM chamber.

4. Results and discussion

4.1. Slump

Fig. 4 demonstrates the continuous decrease in the concrete workability as the fibre volume fraction increases. This trend is evident in concrete mixes containing both steel fibre (STF) and hybrid steel and polypropylene fibre (PPF). When comparing the slump reduction in concrete mixes containing 0.5 %, 0.75 % and 1.0 % STF alongside the hybrid fibre, it is clear that the hybrid fibre LECA concrete exhibits a substantial loss in workability, ranging from 35 % to 93 %. In contrast, the LECA concrete containing only STF shows a workability reduction between 21 % and 79 %.

The observed reduction in slump for the various concrete mixes can be attributed to the increased friction and the associated challenges in achieving uniform distribution due to the geometry of the hooked-end STF. These factors contribute to decreased flowability and ultimately affect workability. In the case of concrete containing hybrid fibre, the complex interactions of the hybrid fibres lead to increased friction within the mix, as the surface texture of PPF creates additional resistance to flow due to possible entanglement and clumping, making it difficult to achieve a uniform and workable mix. Several studies have reported similar effects on concrete workability, for example, Okeh et al., [25] noted a decrease in the workability of self-compacting concrete containing hooked-end STF. Other research also reported comparable findings [26,27].

4.2. Microstructural analysis of ITZ zones for fibre-reinforced LECA concrete

Fig. 5(a), (b) and (c.) illustrate the Interfacial Transition Zone (ITZ)s of the proposed concrete. In Fig. 5a, the ITZ between the LECA aggregate and cement matrix indicate the cement matrix smoothly fused with the LECA aggregate effectively sealing all the pores in the zone. Thereby leading to enhanced bonding and improved mechanical performance. Furthermore, Fig. 5(b) and (c.) show gaps of 0.5–1 μm and 1–2 μm, respectively, between the fibres (STF and PPF) and the cement matrix in the ITZ. Notably, the fibres are not chemically fused to the cement paste as seen in the plain LECA concrete (Fig. 5a). This infers that the bonding of the fibres relies mainly on their mechanical anchorage.

Thus, the ITZ gap in PPF being almost twice in STF concrete indicates the possibility of higher porosity and, consequently, water absorption. This is an important factor considered in formulating the hybrid STF + PPF concrete compositions. The lack of fusion between cement paste and fibre indicates a weaker ITZ for the fibre-reinforced LECA concrete, which means the application of optimal fibre dosage to ensure an enhanced bond.

4.3. Absorption, porosity and dry density

LECA is well-known for its high porosity, which is expected to influence the overall density and water absorption of the resulting concrete. Some of the trapped water within the LECA pores is expected to be released during concrete curing and contribute to the hydration process. However, excessive water absorption can lead to increased porosity in the concrete, potentially affecting its mechanical properties. Furthermore, the relationship between water absorption and concrete porosity can significantly influence thermal

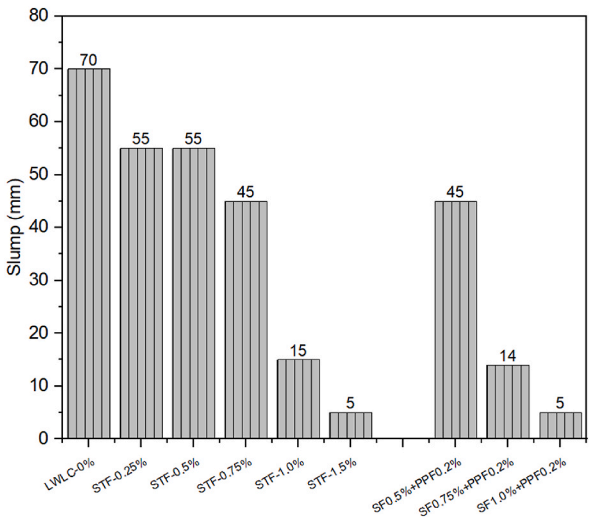

Fig. 4. Slump variation with STF and Hybrid STF + PPF.

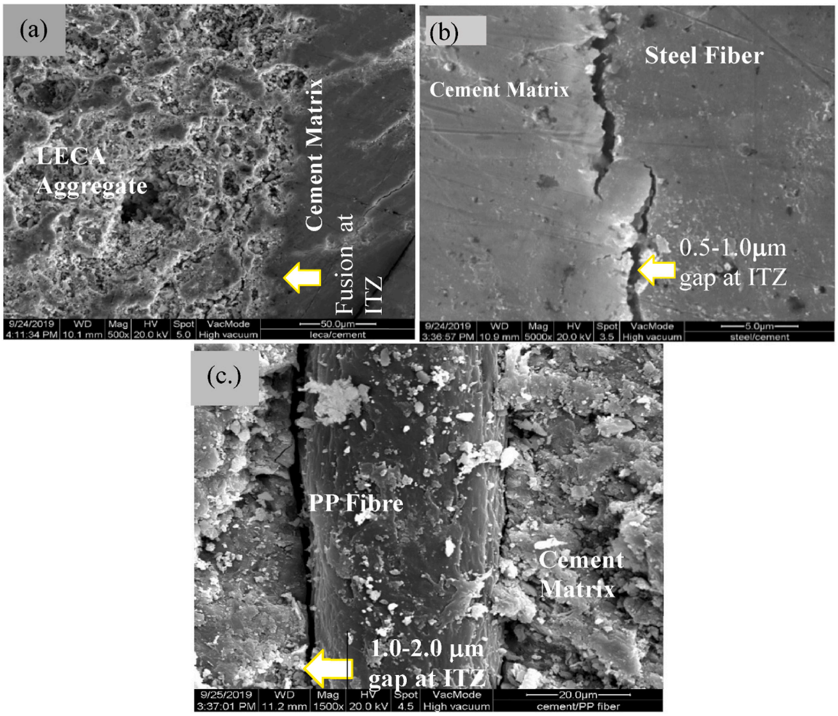

Fig. 5. SEM micrographs showing ITZ of LECA concrete (a) Plain LECA concrete 500x (b) Concrete with STF 5000x (c) Concrete with PPF 1500x

insulation properties and structural performance. Therefore, by thoughtfully designing the concrete mix, it is possible to achieve a balanced relationship among density, porosity and strength in the resulting LECA concrete.

Thus, Fig. 6(a), (b) and (c) illustrate the relationship between porosity, water absorption and density of the fibre-reinforced LECA concrete. As shown in Fig. 6a, the relationship between porosity and water absorption is directly proportional to the increase in fibre content, with higher values observed in concrete containing hybrid fibres. In the case of concrete containing only STF, the increase in fibre content might affect fibre distribution, leading to the formation of voids around the fibres and ultimately increasing the overall porosity of the concrete. It is important to note that the decrease observed in the mix containing 0.25 % and 0.5 % SFT could be attributed to the influence of the GGBFS content, which is acknowledged for its efficiency in reducing capillary pores by promoting the formation of additional C-S-H and also balancing water demand in the concrete.

Subsequently, an increase in porosity and water absorption is observed for several reasons, one of which may be interference caused by the aggregate packing by the hooked-end STF. Similarly, the increase observed in the hybrid fibre LECA concrete (19 % with 0.5 %STF,0.2 %PPF, and 7.2 % with 0.1 %STF,0.2 %PPF) is due to the combined interaction of the fibres which results in a slight increase of the surface area within the concrete mix, in addition to the tendency of the PPF to absorb and retain water further contributes to the overall water increase in water absorption, subsequently leading to higher porosity. This phenomenon is also observed in Fig. 4, which shows the variation in the slump.

While some earlier studies have reported findings consistent with this research [28,29], others have noted opposing findings, for instance, Afroughsabet et al., [30] documented a reduction of up to 23 % in water absorption in high-performance concrete incorporated with recycled aggregate.

Fig. 6b demonstrates a two-stage transition. Firstly, the inclusion of up to 0.5 % STF yields a decrease in porosity with a corresponding increase in density. This phenomenon is attributed to factors such as optimised fibre distribution, which allows enhanced filling of voids and improves the packing density of the concrete. Also, enhanced matrix densification results from an improved interfacial transition zone (ITZ) between the fibre and concrete matrix, thereby reducing porosity and contributing to higher density. Furthermore, the hooked end of the STF provides mechanical anchorage, which enhances the bond strength and reduces microcracking. Secondly, beyond 0.5 %STF, the concrete density continuously increases despite the increase in porosity. This is obviously due to the clustering of fibre at a higher volume fraction, which results in the creation of voids and increased porosity. Moreover, the contribution of the STF's density outweighs the influence of the increased porosity.

A similar trend is observed for hybrid fibre as shown in Fig. 6c, except for a slight drop in density with the introduction of the first fibre dosage.

In comparison to plain lightweight concrete (LWLC), the density consistently increases as fibre content rises in both concrete containing STF and hybrid STF + PPF.

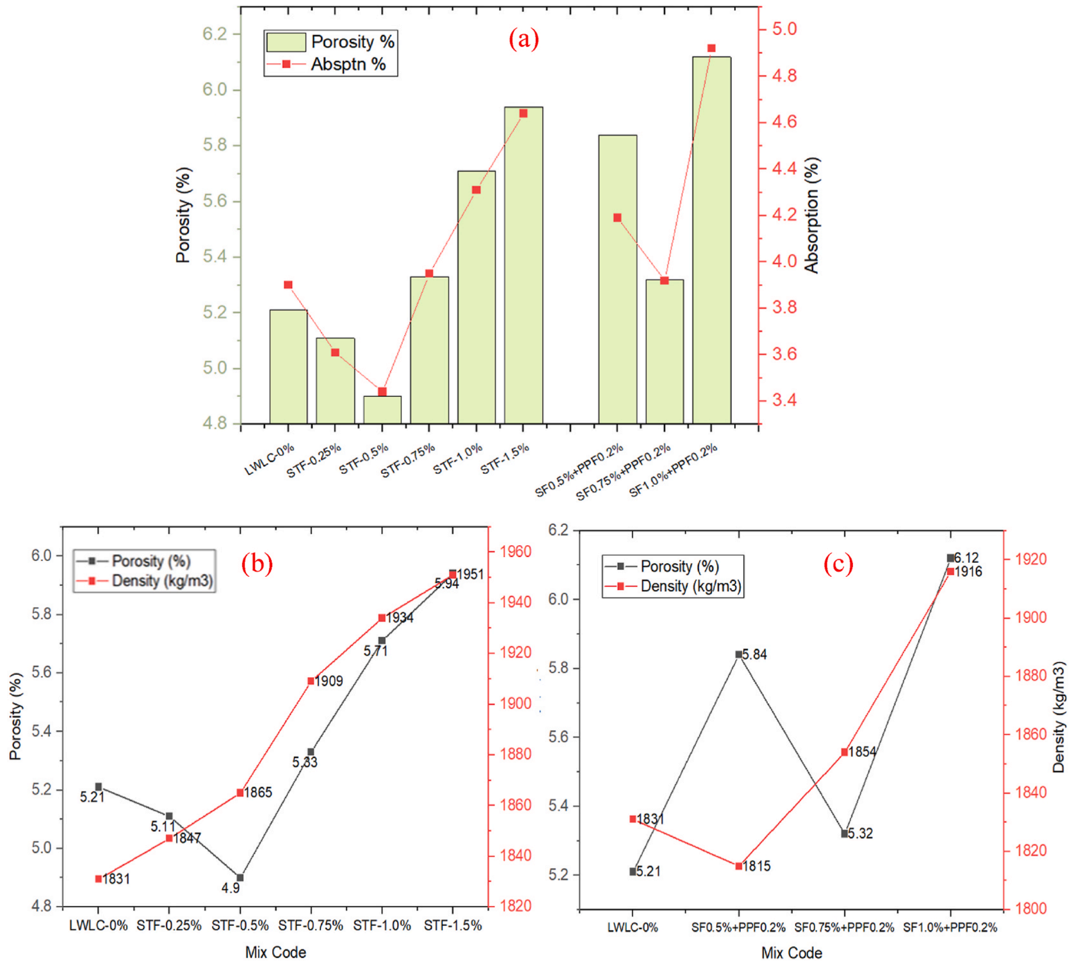

Fig. 6. Variation of: (a) water absorption with porosity of LECA concrete with STF and Hybrid fibre (b) Density with porosity of varying STF reinforced LECA concrete (c) Density with porosity of varying hybrid fibre-reinforced LECA concrete.

4.4. *Compressive strength*

4.4.1. *Influence of hybrid steel fibre*

Fig. 7 (a and b) illustrate the relationship between compressive strength and porosity in relation to variation with STF and hybrid fibre content.

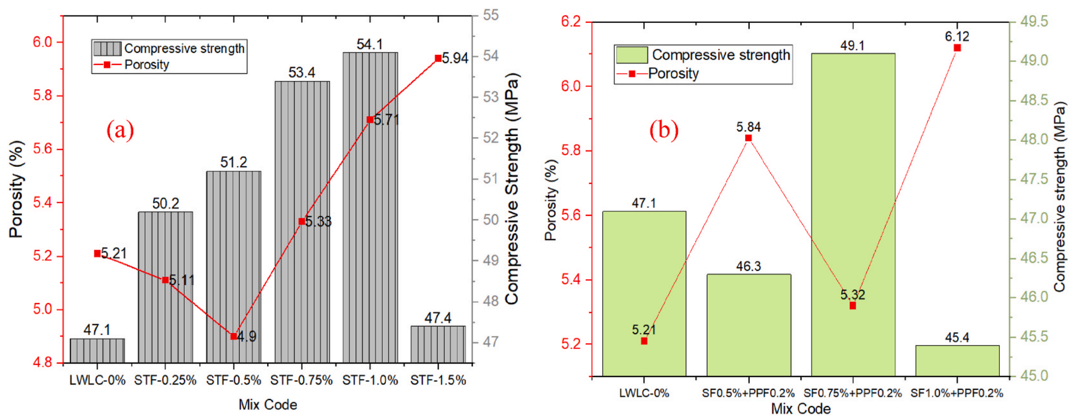

Fig. 7. Variation of compressive strength with porosity for (a) STF-reinforced LECA concrete. (b) Hybrid SFT + PPF-reinforced LECA concrete.

As depicted in Fig. 7a, the incorporation of STF significantly enhances the compressive strength of the control LECA concrete (LWLC), yielding 7 %, 9 %13 %, and 15 % increases, respectively, corresponding to the various fibre volume fractions considered. Conversely, only a 4 % increase was observed for concrete containing 0.75 %SFT+0.2 %PPF, while other dosage combinations led to a slight loss in strength compared to the control sample. The optimum compressive strengths of 54.1 MPa and 49.1 MPa were achieved with 1 %SFT and 0.75 %STF-0.25 % respectively. This indicates a better anchorage between the STF and concrete matrix leading to a consequent increase in compressive strength.

Analysing this improvement in relation to porosity reveals a steady increase in compressive strength, even beyond the optimum porosity (at STF-0.5 %). The observed increase, despite the rising porosity, can be attributed to the efficient bridging effect against crack propagation leading to enhanced overall strength. Moreover, the efficient distribution of load helps reduce the stress concentrations and further bolsters the overall concrete's strength, even in the presence of increased porosity.

In contrast, Fig. 7 (b) shows the influence of hybrid STF + PPF, revealing fluctuations in the compressive strength, with the optimum strength of 49.1 MPa corresponding to a 4 % increase compared to the control sample. In all cases, values of compressive strengths are lower than concrete with 0.5 %,0.75 %, and 1.0 % STF content as shown in Fig. 7a. Unlike the specimen containing only STF, it is evident that compressive strength increases directly with the decrease in porosity.

While the continuous increase due to the hooked-end STF is anticipated, the decrease caused by the hybrid fibre was unforeseen. Nonetheless, close observation of the diverse fibre properties suggests the drop in compressive strength could be attributed to several factors, including fibre interaction, distribution, fibre volume fraction, and microstructure. The combination of SFT and PPF leads to poor interaction between the fibres and the concrete matrix, resulting in weaker bonding and an overall reduction in strength. In addition, this might have also affected the uniform distribution and orientation within the concrete mix. Additionally, the combined fibre content might exceed the optimal content, leading to a decrease in workability and compaction, with consequent voids and weak spots. Several studies have reported significant improvement in compressive strength with STF [31,32] and hybrid STF with PPF [33,34].

4.4.2. *Predictive models of compressive strength based on porosity*

Understanding the relationship between porosity and compressive strength of LECA concrete is important for developing a reliable prediction model that can enhance quality control, optimisation, and cost efficiency, ensure durability, and minimize environmental impact. With this in mind, predicting compressive strength based on porosity has the potential to reduce the need for extensive and costly testing.

Thus, Fig. 8 illustrates these relationships for the LECA concrete containing SFT and hybrid STF + PPF. The high coefficients of determination $R^2 = 0.9857$ and 0.9864 as shown on the plots indicate that the proposed polynomial and linear models account for 99 % variation in the compressive strength values for concrete with SFT (Equation (1)) and hybrid fibre (Equation (2)) respectively. It is important to note that Equation (1) is valid for $STF \leq 1.5\%$, while Equation (2) is valid for $STF \leq 1\%, and\ PPF \leq 0.2\%$, all within a temperature range of $0 - 50C^0$.

$$f_{stf} = -52.44x^3 + 834.85x^2 - 4417.42x + 7821.57 \tag{1}$$

$$f_{stf+ppf} = -4.72 + 74.13x \tag{2}$$

f_{stf} is the compressive strength of concrete mix containing only STF, $f_{stf+ppf}$ is for concrete containing hybrid fibre, while x stands for the concrete porosity.

Previous studies have reported an exponential relationship between compressive strength and density [7]. Nonetheless,

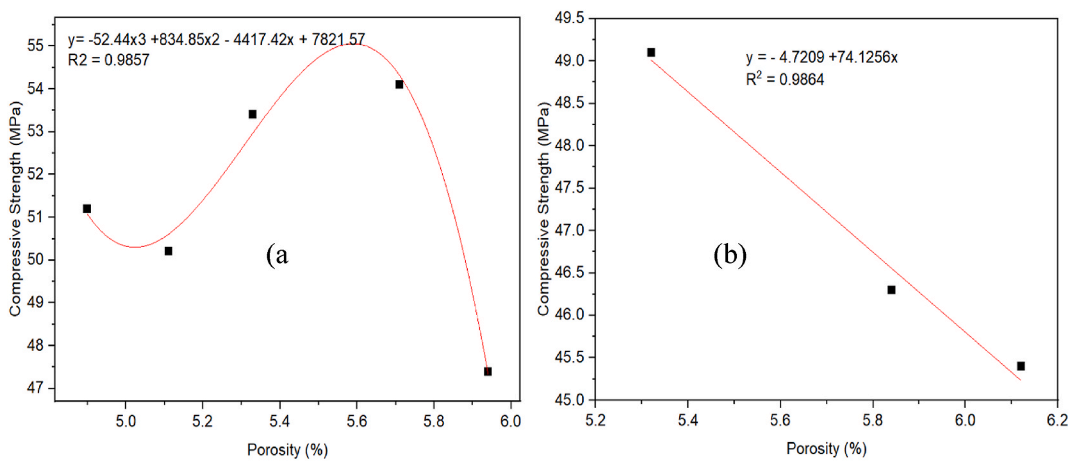

Fig. 8. Relationship between porosity and compressive strength for (a) STF-reinforced LECA concrete. (b) hybrid STF and PPF-reinforced LECA concrete.

considering the relationship between density and porosity, this can be correlated.

4.5. Split tensile strength

4.5.1. Influence of hybrid steel fibre with polypropylene on split tensile strength

A good understanding of the split tensile strength of the fibre-reinforced LECA concrete is crucial for ensuring predicting performance, structural integrity, crack resistance and most importantly, the safety and reliability of the concrete structure.

In line with this, Fig. 9 shows the variation of split tensile strength of the LECA concrete with varying STF and hybrid fibre content. In each case, a continuous increase in the tensile strength is observed with each increase in fibre content, with up to 131 % increase with 1 %SFT and 45 % with hybrid STF-1 % + 0.2 %PPF when compared with the control sample. Furthermore, comparing the two concrete mixes (i.e, STF and hybrid), a reduction of 17 %, 36 % and 37 % were observed in concrete containing hybrid STF-0.5 %+PPF-0.2 %; STF- 0.75 %, PPF-0.2 %; and STF-1.0 %, PPF-0.2 % hybrid fibre.

The influence of porosity on the strength followed the same trend as it is with the compressive strength of the SFT specimen. However, in contrast, the behaviour of the specimen produced with hybrid fibre seems to be more influenced by the fibre content instead of the porosity, thus showing a continuous increase with the increase in increase in fibre content.

The enhanced tensile strength observed in the concrete containing only STF is due to the strong mechanical bond that exists between the STF and concrete matrix resulting from the shape which helps in effectively transferring stress and the tensile strength. In contrast, PPF have a lower modulus of elasticity and weaker bonding with the concrete which reduces the overall tensile strength of the concrete when combined with steel fibres. This infers that the STF are more efficient in distributing stress and bridging cracks within the concrete matrix. Similar results have been established in lightweight pumice concrete [35], and other concrete types [36,37].

4.5.2. Predictive models for split tensile strength based on porosity

The porosity is an important factor in analysing the mechanical properties of lightweight concrete since it directly influences the change in density of the concrete. Thus, predicting the mechanical properties of the LECA concrete by considering porosity as a variable will be beneficial, particularly in terms of cost and time, in addition to exploring a better understanding of the overall LECA concrete tensile behaviour.

The relationship between porosity and split tensile strength is represented in Fig. 10. The R^2 of 1 for both concrete mixes indicate a strong relationship, demonstrating the capability of the developed polynomial and quadratic models (3) and (4) to be utilised for the prediction of the split tensile strength of LECA concrete containing STF and STF + PPF respectively. Validity of Equation (3) is for $STF \leq 1.5\%$, while Equation (4) is valid for $STF \leq 1\%, and\ PPF \leq 0.2\%$, all within temperature range of $0 - 50C^0$.

$$f_{(st)stf} = 75.06x^4 - 1634.29x^3 + 13320.68x^2 - 48167.89x + 65198.08 \quad (3)$$

$$f_{(st)stf+ppf} = 2.95x^2 - 33.56x + 98.22 \quad (4)$$

Where, $f_{(st)stf}$ and $f_{(st)stf+ppf}$ Stands for split tensile strength of the concrete with STF and hybrid fibre respectively.

4.6. Thermal properties

This section presents an analysis of the thermal properties of the fibre-reinforced LECA concrete consisting of GGBFS. Each thermal property is discussed in relation to fibre content, porosity and varying temperature (0–50 °C).

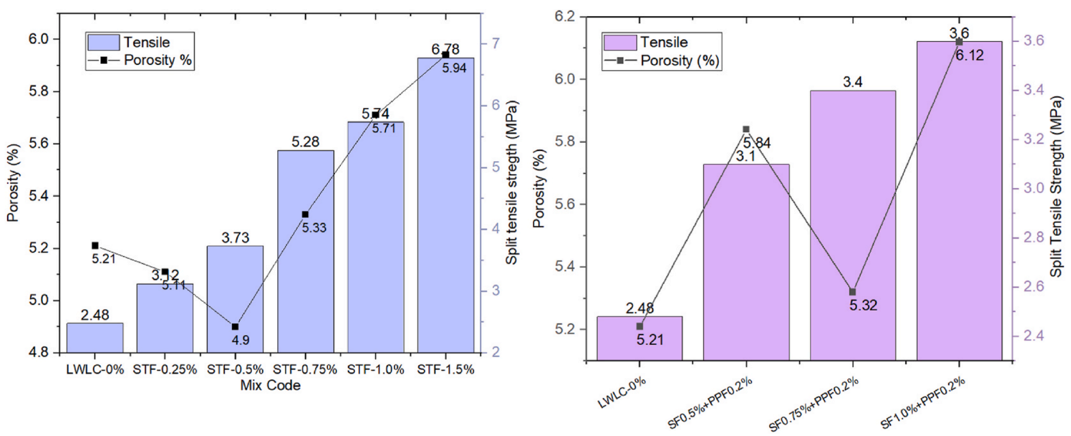

Fig. 9. Variation of Split Tensile Strength with varying porosity in LECA concrete with (a) STF (b) STF + PPF.

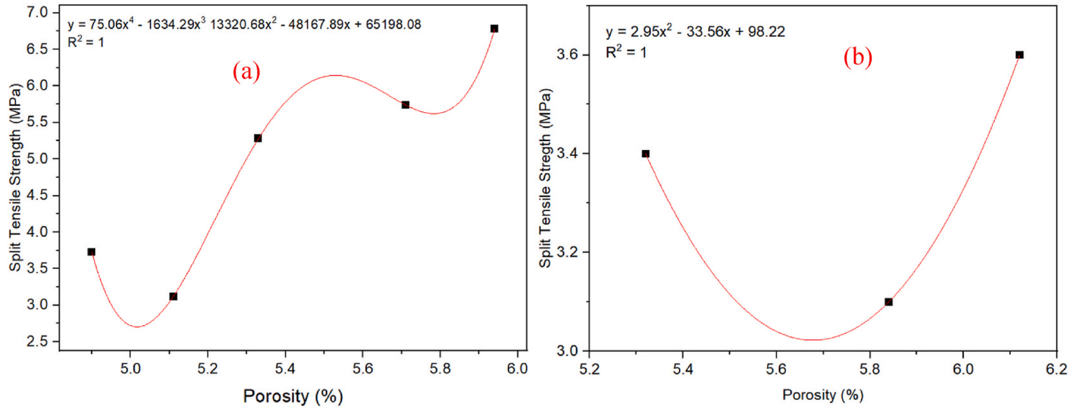

Fig. 10. Relationship between split tensile strength and porosity for LECA concrete containing (a) STF (b) STF + PPF.

4.6.1. *Influence of STF and hybrid STF + PPF on thermal properties of LECA concrete*

A close observation of Fig. 11 (a) reveals, that except for the 1 % drop in specific heat (SH) exhibited by concrete containing 0.25 % STF, the thermal properties of all concrete containing STF outperform those of the control sample (LWLC). The highest Thermal conductivity (TC) and Diffusivity (TD) of 1.4276 W/m K and 0.934 mm^2/s was achieved with 1 %STF. This is equivalent to 24 % and 21 %increase respectively. Additionally, the maximum values recorded for thermal effusivity and specific heat were 1520.86 $Jm^{-2}K^{-1}S^{-1/2}$ and 876.21 J/kg.K, reflecting an increase of 16 % and 6 %, respectively, compared to the LWLC.

However, it is important to note that as the STF content increases their distribution and orientation within the concrete matrix changes leading to variation in the thermal pathways and overall TC and TD as observed. Additionally, the interfacial thermal resistance between the STF and concrete mix also influences the thermal properties of the concrete. The increase is associated with the thermal bridging of the STF, while the decrease is due to disruption in matrix continuity. These combined effects on TC impact the thermal inertia, and consequently the TE and SH. This indicates that the interplay between STF and concrete matrix is typically nonlinear, leading to unexpected changes in thermal behaviour.

The implications for thermal efficiency suggest that concrete with reduced TC and TD can serve as better insulators due to reduced heat transfer, leading to lower energy consumption for heating and cooling. Conversely, concrete exhibiting higher SH and TE will be beneficial in applications where maintaining stable indoor temperatures is crucial. This can also reduce the reliance on active heating and cooling systems. The dynamic response means STF can be utilised for tailored performance.

Lower SH means that the concrete responds rapidly to changes in temperature by heating up and cooling down faster compared to other concrete mixes with higher specific heat. On the other hand, lower TE means efficient thermal insulations by maintaining stable indoor temperatures since it is less effective in absorbing and releasing heat.

Fig. 11b shows a continuous increase in the thermal properties of concrete containing hybrid fibre with optimal properties obtained with 0.75 %STF+0.2 %PPF and declines afterwards. When compared with the properties of STF concrete as in Fig. 11a, the use of hybrid concrete results in a reduction in thermal properties of up to 13 % in TC, 12 % in TD and 9 % and 2 % in TE and SH respectively.

For easier reference, Fig. 12 (a) and (b) illustrate the combined thermo-mechanical relationship between STF and hybrid STF + PPF LECA concrete. The plots aimed to provide a general influence view on all the responses in one figure, giving the reader the leverage to

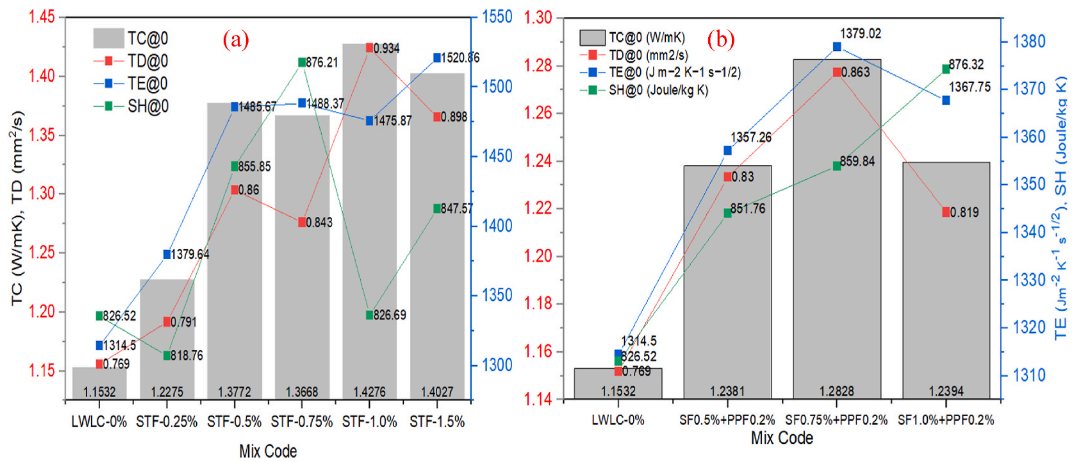

Fig. 11. Influence of (a) SFT and, (b) hybrid STF + PPF content on Thermal properties of LECA concrete.

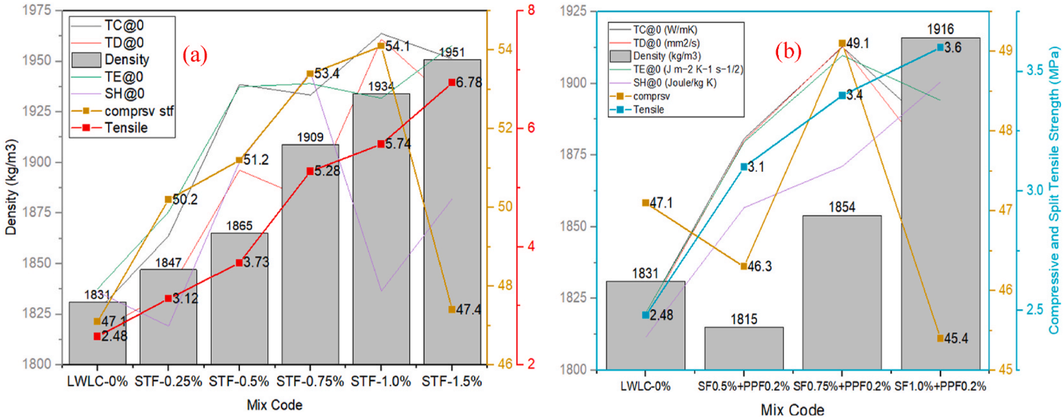

Fig. 12. Relationship between density, compressive strength and Thermal Properties.

ponder on the suitable mix depending on the intended application (s). At a glance, one should be able to make a concise decision depending on which property is a priority.

4.6.2. Influence of porosity on thermal properties of LECA concrete

The porosity of concrete is acknowledged to significantly influence its thermal properties, because the air-filled pores act as insulators, thereby reducing the concrete's ability to conduct heat. However, the porosity is nonetheless very influential in actualising the low concrete density sort for in modern design. Thus, subsequent sections explore the influence of LECA concrete porosity on thermal conductivity, thermal diffusivity, thermal effusivity and specific heat of concrete.

4.6.2.1. LECA concrete reinforced with STF. Thus Fig. 13, illustrates the variation of thermal properties with varying porosity for LECA concrete with STF. The porosity of concrete containing STF is higher than the control and increases with an increase in STF content. A significant decrease in thermal properties is observed with an increase in porosity, that is, between specimens containing 0.5 %STF and 0.25 %STF and subsequently fluctuating. Sample 0.5 %STF has the lowest porosity, followed by 0.25 %STF which corresponds to a 6 % and 4 % reduction in porosity when compared with the control sample (LWCL).

The initial reduction in porosity is due to the ability of the STF to effectively distribute load more evenly during compaction, thus evenly dissipating trapped air within the voids, thereby decreasing porosity. Furthermore, the trend can be attributed to the enhanced bonding leading to denser concrete with reduced porosity. However, fluctuations in thermal properties between 0.75 %STF and 1.0 % STF are observed with the increase in porosity. Nonetheless, minimum values of thermal properties are observed in concrete containing 0.25 %STF while the highest values of TC, and TD are from 1 %STF, SH in 0.75 %STF and TE in 1.5 % respectively.

Thus, based on the observed variations in properties, an informed decision to guide improved energy efficiency can be derived while ensuring low density and enhanced mechanical properties. Moreover, while concrete mix with lower thermal properties might be advantageous for energy-efficient buildings, higher thermal properties are beneficial for industrial facilities such as power plants, furnaces, and kilns.

4.6.2.2. LECA concrete reinforced with hybrid STF + PPF. Fig. 14 shows variation in thermal properties for concrete containing hybrid

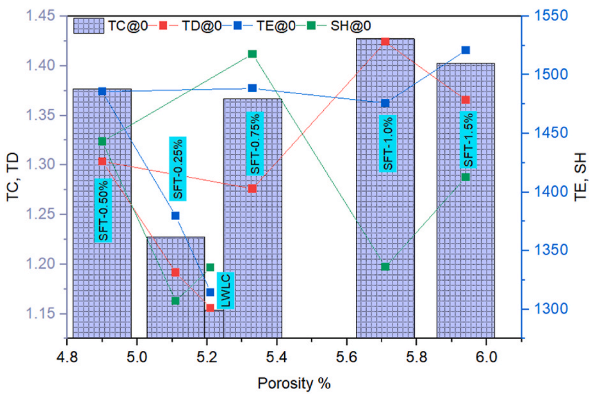

Fig. 13. Variation of thermal properties with porosity for LECA concrete containing STF Fibre.

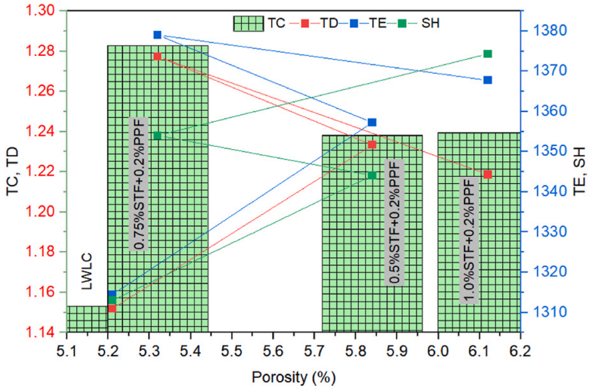

Fig. 14. Variation of thermal properties of LECA concrete containing hybrid fibre with porosity.

STF + PPF. The porosity here appeared slightly higher than that observed in concrete containing STF as depicted in Fig. 13.

The result indicates increasing thermal properties with increasing porosity resulting from increased fibre content. While the highest thermal properties were observed in concrete containing hybrid 0.75 %STF+0.2 %PPF, concrete produced with 0.5 %STF+0.2 %PPF yielded the lowest values despite having higher porosity. The reduction observed is the ability of the PPF to reduce the inherent higher TC of the steel fibre, resulting from changes in the spalling resistance. In each case, the TE is higher, followed by TC, TD, and SH, respectively, suggesting an enhanced thermal property. Other studies have indicated a similar relationship [38,39].

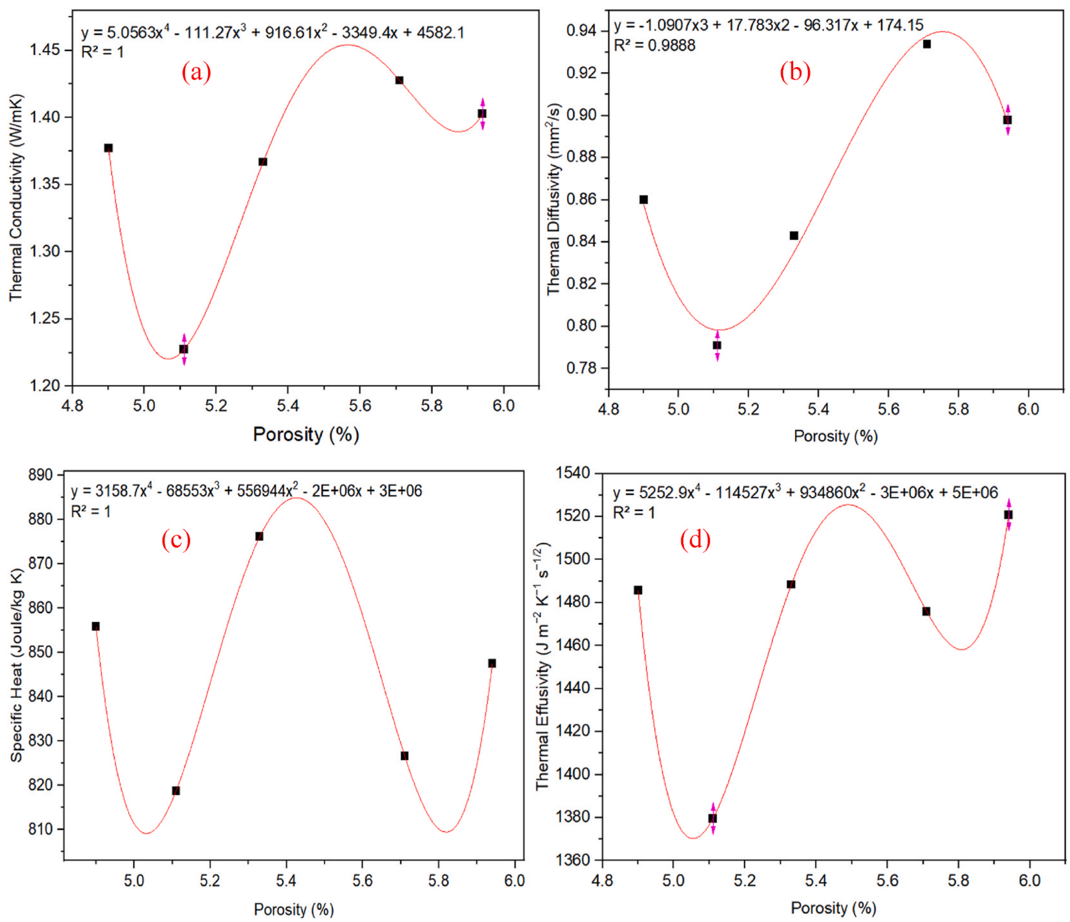

Fig. 15. Relationship between thermal properties and porosity of STF reinforced LECA concrete (a) Thermal conductivity vs Porosity (b) Thermal diffusivity vs porosity (c) Specific Heat vs porosity (d) Thermal Effusivity vs porosity.

4.6.3. Predictive models for thermal properties of LECA concrete

This section presents relationships between individual thermal properties of the fibre-reinforced LECA concrete incorporated with STF and hybrid fibre respectively.

4.6.3.1. Relationships between porosity and thermal properties of LECA concrete with STF. Fig. 15 (a, b, c, and c) demonstrate the relationship between porosity and individual thermal properties of LECA concrete. Considering the heterogeneity of the concrete, the developed models revealed polynomial relationships for all the properties, with a higher coefficient of determination (R^2) ranging from 0.99 to 1. This indicates a strong correlation between these properties and porosity and that almost 99 %–100 % of the variation has been accounted for by the proposed models. This further indicates the validity of the models for the prediction of thermal properties of fibre-reinforced LECA concrete. Equations (5)–(8) are proposed for thermal conductivity (TC), Thermal Diffusivity (TD), Specific Heat (SH), and Thermal Effusivity (TE). Equations (5)–(8) are valid for $STF \leq 1.5\%$ within a temperature range of $0 - 50C^0$.

$$TC = 5.0563x^4 - 111.27x^3 + 916.61x^2 - 3349.4x + 4582.1 \quad (5)$$

$$TD = -1.0907x^3 + 17.783x^2 - 96.317x + 174.15 \quad (6)$$

$$SH = 3158.7x^4 - 68553x^3 + 556944x^2 - 2E + 06x + 3E + 06 \quad (7)$$

$$TE = 5252.9x^4 - 114527x^3 + 934860x^2 - 3E + 06x + 5E + 06 \quad (8)$$

4.6.3.2. Relationships between porosity and thermal properties of LECA concrete with hybrid STF + PPF. Unlike the relationship observed for concrete containing only STF, the relationship in Fig. 16 is observed to be mostly quadratic and linear while maintaining a strong correlation with R^2 values between 0.99 and 1. The proposed models for predicting the thermal properties are presented in equations (9)–(12) for TC, TD, TE and SH respectively with respect to the concrete porosity. Considering the technicality and time (at least 2 h for thermal conductivity) involved in conducting the thermal properties test, the developed models offer several advantages in terms of simplifying the method for the determination of LECA concrete thermal properties. Equations (9)–(12) are valid for a hybrid

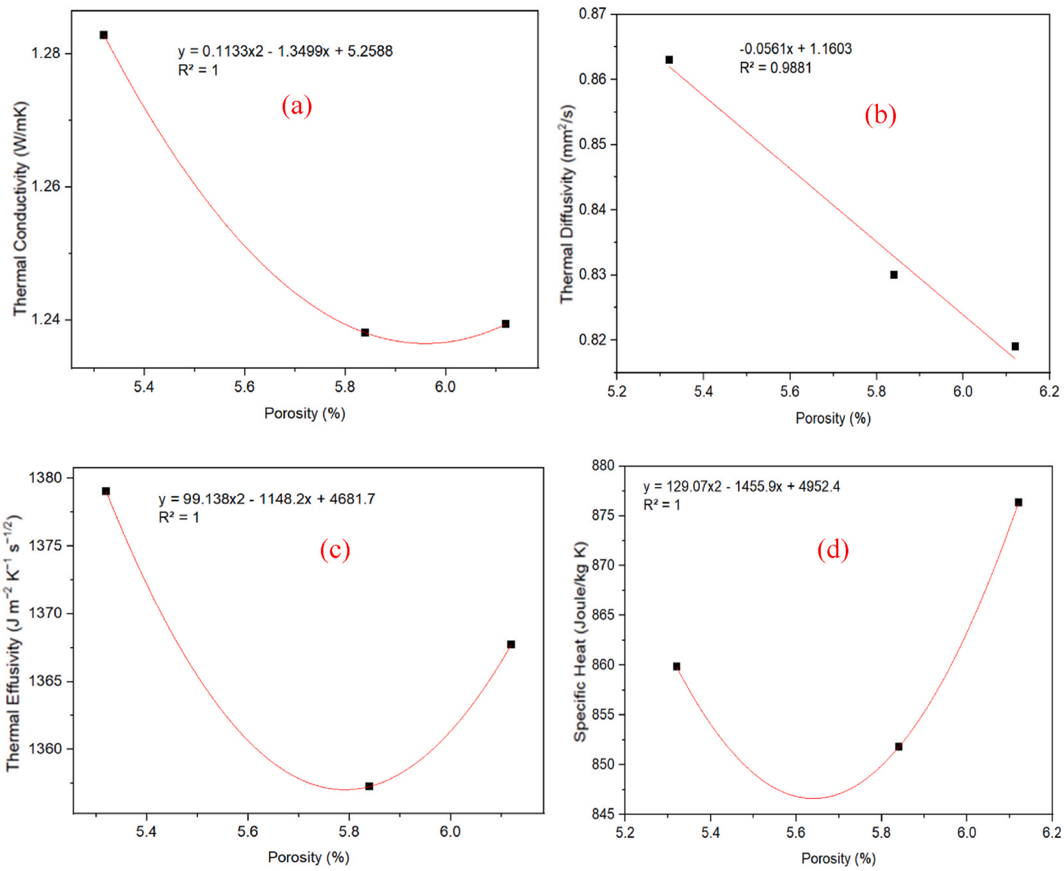

Fig. 16. Relationship between thermal properties and porosity of hybrid fibre-reinforced LECA concrete(a) Thermal conductivity vs Porosity (b) Thermal diffusivity vs porosity (c) Thermal Effusivity vs porosity(d) Specific Heat vs porosity.

combination of $STF \leq 1\%, and\ PPF \leq 0.2\%$ within a temperature range of $0 - 50C^0$.

Other studies relate this relationship in terms of density [7,40], but it appears more appropriate to represent this relationship in terms of porosity since it has a direct relationship with the density and thermal properties, and is directly proportional to the trapped air with the concrete voids.

$$TC = 0.1133x^2 - 1.3499x + 5.2588 \tag{9}$$

$$TD = -0.0561x + 1.1603 \tag{10}$$

$$TE = 99.138x^2 - 1148.2x + 4681.7 \tag{11}$$

$$TC = 129.07x^2 - 1455.9x + 4952.4 \tag{12}$$

4.6.4. Influence of temperature on thermal properties of LECA concrete

Understanding the thermal behaviour of the proposed concrete will help in designing resilient buildings with stable indoor temperatures. Leveraging these properties aligns with sustainability practices for reducing the environmental impact of construction materials.

4.6.4.1. Thermal conductivity and diffusivity. Fig. 17 (a), and (b) show the variation of thermal conductivity (TC), whereas Fig. 17 (c.) and (d) demonstrate the variations of thermal diffusivity (TD) of LECA concrete with varying temperatures (0–50 °C). The TC is defined as the amount of heat transferred through a square area of material, with typical values ranging between 0.51 and 1.33W/mk reported for dense concrete blocks [41]. Thus, the lower the TC, the less energy is transferred and the better it is as an insulator. In this case, observing Fig. 17 (a) and (b) reveals a continuous decrease in the thermal conductivity with the temperature rise, which can be attributed to several factors, such as loss of free water, changes in aggregate property and variation in microstructural changes. Because at higher temperatures the free water within the LECA and concrete evaporates, thereby reducing the conductivity. Also, the increase in temperature might result in microstructural changes such as increased porosity and microcracking thereby leading to low heat transfer. Nonetheless, comparing concrete containing 0.5 %, 0.75 % and 1.0 % STF in both concretes reveals reductions in the TC by 10 %, 6 % and 13 % resulting from the inclusion of PPF. The maximum thermal conductivity observed is 1.4276 W/(mK) and the minimum is 1.1251. While the max and min for hybrid fibre are 1.2828 and 1.1902 W/(mK) respectively.

Conversely, a general increase in thermal conductivity is observed with each rise in both STF and hybrid fibre when compared with plain LECA concrete (LWLC). This is expected due to the high thermal conductivity of the steel fibre (STF). The highest TC are observed in concrete produced with 1 %STF and hybrid 0.75 %STF +0.2 %PPF respectively.

The results infer different ranges of applications for the ranges of TC, while lower TCs will be suitable for residential buildings and other related applications, higher TCs will be advantageous for industrial structures. Other studies, including attributed these variations to an increase in the air gap between the fibre–cement interfacial zone, leading to a decrease in the thermal conductivity [40]. Similarly, the loss of conductive bond in concrete destruction of physically and chemically bound water. In addition, several studies have reported a similar trend of decreased TC at even higher temperatures, in addition to the significant influence on the distribution of temperature and heat flux vector of the concrete [42,43].

The thermal diffusivity (TD) of the concrete refers to the measure of how quickly heat spreads through it. High TD indicates how quickly the concrete adjusts its temperature in response to variations in the surrounding temperature. As shown in Fig. 17(c) and (d), the TD follows a similar trend as observed in the TC for both STF and hybrid fibre concrete. Increasing with an increase in fibre dosage and decreasing as the temperature increases. This shows a strong correlation which varies in direct proportion between TC and TD. Furthermore, it can also be inferred that the proposed LECA concrete can maintain structural integrity under thermal stress since it can quickly dissipate heat and prevent localised heating.

The study on the variation of thermal diffusivity is limited, but few studies including Shafigh et al., [40] and Heek et al., [44] reported a similar relationship for steel fibre-reinforced concrete.

4.6.5. Specific heat and thermal effusivity

Specific heat of concrete refers to the energy per unit of mass that is needed to raise its temperature by one degree [45,46]. Thus, the higher the SH of the concrete, the more energy is needed in order to increase its temperature. Based on this, a combination of higher SH, density and reasonable TC offers a useful level of thermal mass (i.e. the ability of the concrete to protect against temperature changes by absorbing and releasing heat). The average specific heat of dense concrete block is between 800 and 1000 J/kg K [41].

Fig. 18(a) and (b), show variation of specific heat, while Fig. 16 (c) and (d) show thermal effusivity of the LECA concrete with temperature. The specific heat is observed to increase with the increase in temperature for both concretes with STF and hybrid fibre. The SH of concrete produced with STF operating within the considered temperature varies from 819 to 974 J/kgK, while that containing STF + PPF ranges between 852 and 1004 J/kgK. The variation in properties due to an increase in temperature is between 1 and 6 % for STF concrete and between 1 and 5 % for hybrid fibre concrete for every 10-degree rise in temperature, with the maximum variation observed in the plain LECA concrete.

The reason for the inclusion of polypropylene fibre can be seen to yield high SH, which is due to the microstructural influence of the PPF to distribute heat within the concrete mix, thereby enhancing its ability to store thermal energy. In addition, the synergistic effects between the two fibres improve the thermal performance of the concrete [40,47].

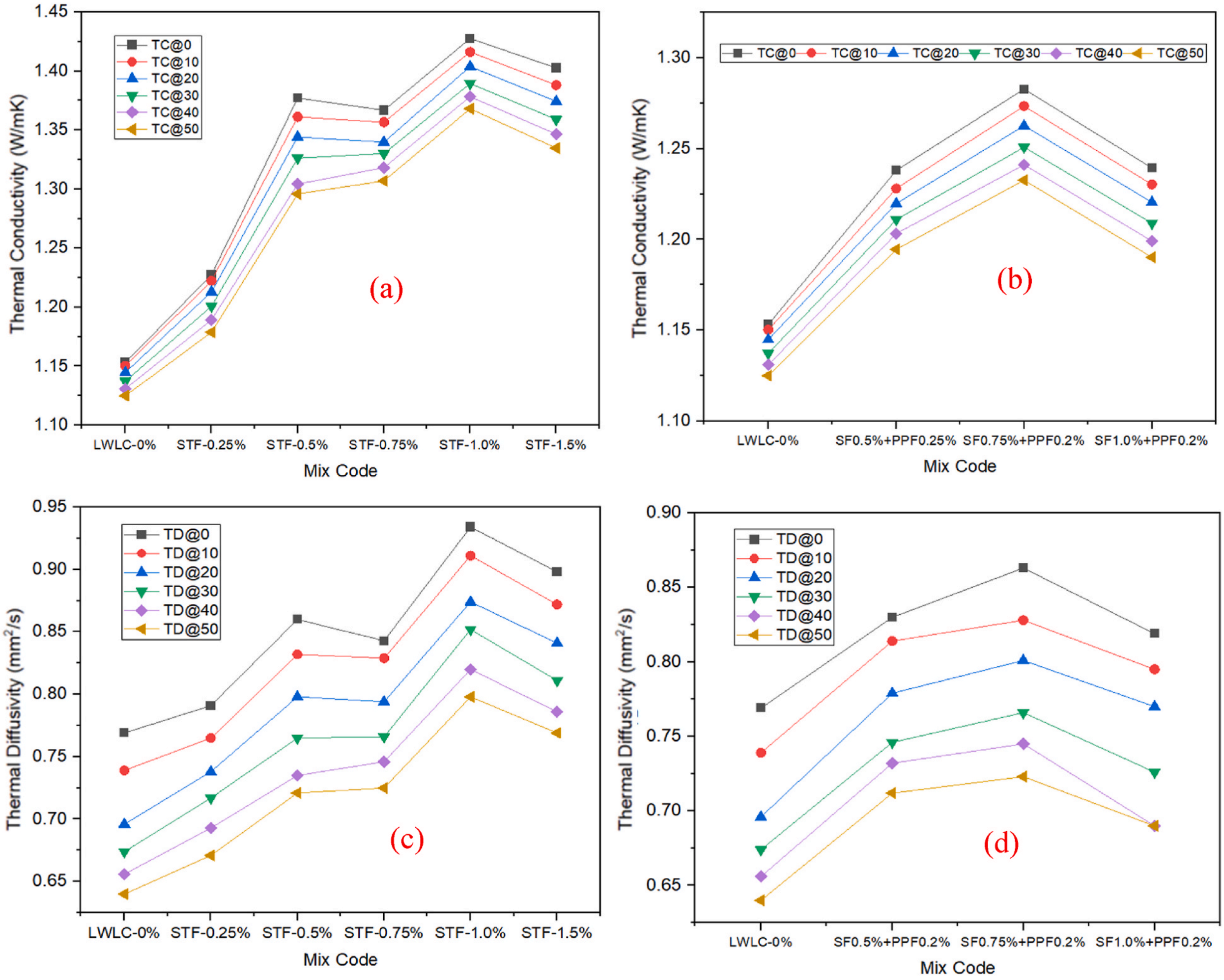

Fig. 17. Variation of thermal conductivity and thermal diffusivity of LECA concrete with temperature.

This infers that concrete produced with hybrid fibre is advantageous since having higher SH infers that the concrete can absorb and store more heat energy before its temperature rises significantly. In other words, it will serve as a better insulator for building materials to ensure stable temperatures.

The thermal effusivity of concrete is the measure of the concrete's ability to exchange heat with its surroundings. Typically, the values range between 800 and 1600 J m^{-2} K^{-1} $s^{-1/2}$ which varies depending on the heterogeneity and density of the concrete. Fig. 18 (c.) and (d) show a continuous increase in the thermal effusivity of the concrete with an increase in temperature in both concrete containing different fibre volume fractions. A significant increase is observed compared to the plain LECA concrete. This also indicates a strong correlation between the SH and TE since the TC and density of the concrete are considerably favourable. Thus making it effective in exchanging heat with its surroundings.

5. Conclusions

The study investigated the thermo-mechanical performance of lightweight fibre-reinforced LECA concrete. The natural aggregate in the concrete mixes was entirely replaced with LECA, and 13 % of the cement was replaced with GGBFS to enhance the mix and reduce the carbon footprint in the resulting concrete. Concrete mixes containing steel fibre (STF) and hybrid steel (STF) with Polypropylene fibre (PPF) at different varying volume fractions were considered (STF: 0.25 %, 0.5 %, 0.75 %, 1.0 % and 1.5 %; STF + PPF: 0.5 % + 0.2 %; 0.75 % + 0.2 %; and 1.0 % + 0.2 %). The physical properties of the concrete, including porosity, water absorption and density were assessed. Additionally, the mechanical properties, specifically compressive and split tensile strength were also evaluated. Thermal properties for each concrete were tested using a Fox50 series heat flow meter. The combined results were evaluated based on fibre content, porosity and temperature of between 0 °C–50 °C.

The following are conclusions derived from the findings.

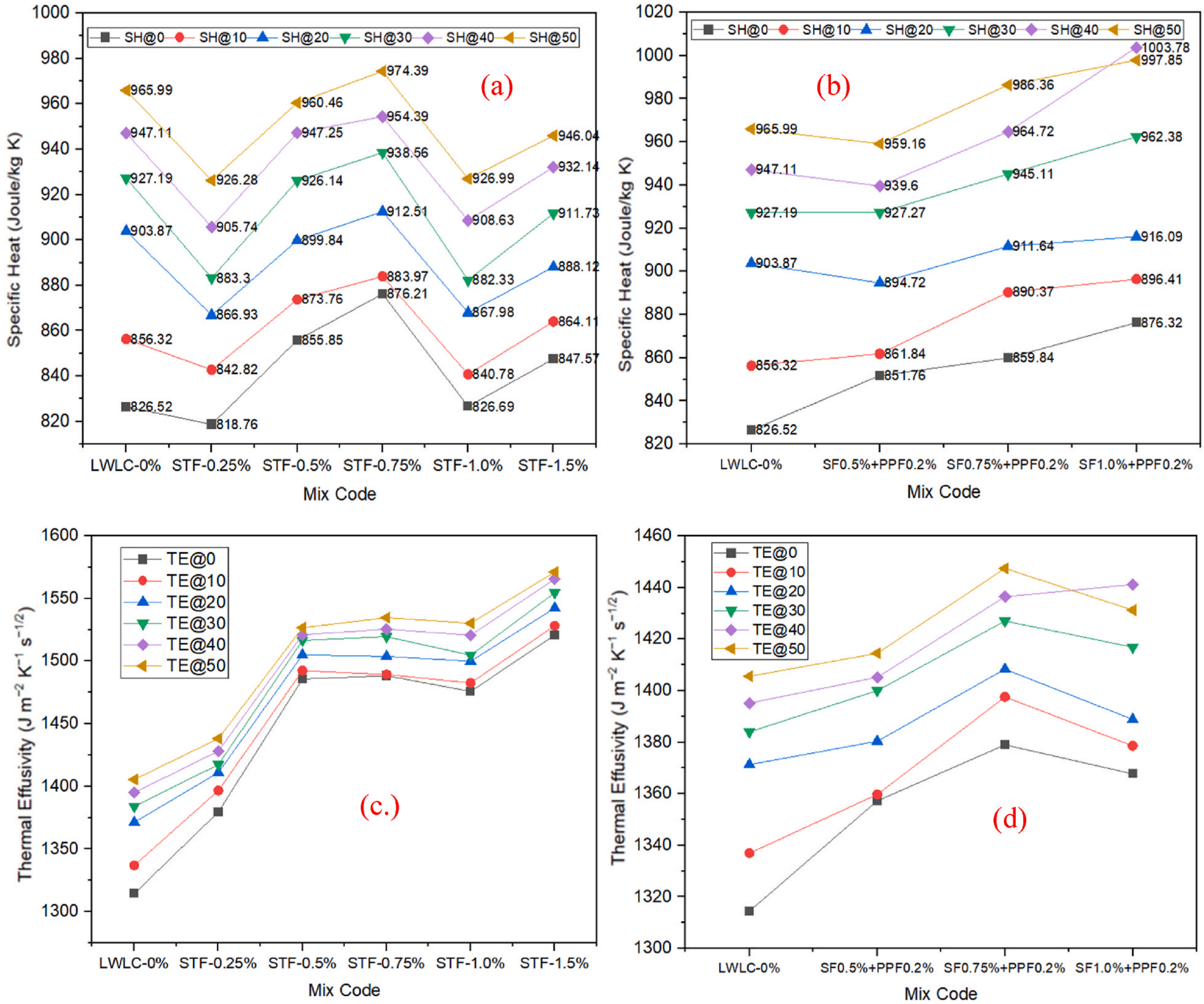

Fig. 18. Variation of Specific Heat and Thermal Effusivity of LECA concrete with varying temperature.

- ✓ LECA concrete produced with hybrid STF + PPF demonstrates a significant reduction in workability, ranging from 35 % to 93 % compared to a range of 21 %–79 % for STF concrete.
- ✓ A higher gap at the interfacial Transition zone (ITZ) is exhibited with the inclusion of PPF, leading to increased porosity and water absorption. The average ITZ size with hybrid fibre is about 1.5 times greater than that observed with STF alone.
- ✓ Density increases with higher fibre content, even as porosity increases.
- ✓ The optimum compressive strength is achieved at 1 %STF and 0.75 %STF+0.2 %PPF, while a steady increase in split tensile strength is observed across both fibre compositions.
- ✓ Fluctuations in thermal properties are observed when STF >0.5 %, specifically an increase in thermal conductivity and diffusivity, indicating poorer insulating properties at higher STF content. Nonetheless, these fluctuations can be leveraged for tailored engineering applications where specific thermal properties are essential.
- ✓ Concrete produced with hybrid fibre displays stable thermal response up to 0.75 %STF+0.2 %PPF. The thermal conductivity and diffusivity are considerably lower than those observed with STF alone, indicating enhanced insulation properties and greater potential for enhanced energy consumption and efficiency.
- ✓ The predictive models developed are capable of forecasting the thermo-mechanical behaviour of LECA concrete, evidenced by the coefficients of variation (R^2) between 0.99 and 1.
- ✓ In both concrete types, thermal conductivity and diffusivity decrease as the temperature rises from 0 - 50 °C, demonstrating the concretes' ability to transmit less heat at higher temperatures and thus highlighting its efficient thermal performance.
- ✓ Thermal effusivity and specific heat increase with rising temperature, suggesting the concrete's ability to absorb and store heat energy before a significant rise in the internal temperature of the building. These characteristics contribute to energy savings and reinforce the strong correlation between thermal effusivity and the specific heat of the concrete.

✓ Thus, this concrete is highly effective as a building envelope, enhancing insulation and reducing energy demands for heating and cooling, particularly in regions with extreme temperatures.

CRediT authorship contribution statement

Idris Ahmed Ja'e: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Zakaria Che Muda:** Writing – original draft, Visualization, Supervision, Project administration, Conceptualization. **Chiemela Victor Amaechi:** Writing – original draft, Validation, Software, Formal analysis. **Hamad Almujibah:** Visualization, Resources, Funding acquisition, Formal analysis. **Agusril Syamsir:** Supervision, Project administration, Data curation. **Teh Hee Min:** Writing – review & editing, Validation, Project administration, Investigation. **Ali E.A. Elshekh:** Resources, Funding acquisition, Data curation. **Maaz Osman Bashir:** Resources, Funding acquisition, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Hamad Almujibah reports article publishing charges was provided by Taif University. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors do not have permission to share data.

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