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Modelling and optimisation of the structural performance of lightweight polypropylene fibre-reinforced LECA concrete

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ABSTRACT

Lightweight fibre-reinforced concrete integrates the advantages of lightweight aggregates with the strength-enhancing properties of fibres, resulting in a lighter composite with enhanced impact and mechanical performance. However, achieving an optimal balance between structural weight, and performance remains a challenging endeavour. This study investigates the mechanical properties, impact energy absorptions, flexural toughness, and crack resistance of lightweight fibre-reinforced concrete with the coarse aggregate entirely replaced with lightweight expanded clay aggregate (LECA). Concrete mixes containing 0 %, 0.5 %, 0.75 %, and 1.0 % Polypropylene fibre (PPF) and 10 % micro-silica were experimentally investigated. Predictions for concrete mixes with up to 2 % PPF were made using regression models developed from experimental data. The experimental and predicted results were analysed using response surface methodology. The findings reveal significant enhancements of up to 300 % and 570 % in toughness indices I_5 and I_{10} at 1 % PPF, coupled with a 55.4 % increase in residual strength. Furthermore, an optimised slab thickness of 47 mm containing 1.73 % PPF yielded optimal impact energy absorption of 680 J and 2384 J and crack resistance of 3823 MPa and 16279 MPa at service and ultimate loading, respectively. These metrics represent improvements of 4.8, 15.2, 37, and 56 times, respectively, compared to the control samples. These substantial advancements highlight the potential of lightweight fibre-reinforced LECA concrete in engineering applications where balancing impact energy absorption, crack resistance, and structural weight is crucial. This innovative approach promises a transformative impact on the construction industry, paving the way for more efficient and resilient infrastructure.

1. Introduction

Lightweight concrete has been a versatile construction material for decades, with its origin dating back to 273 BC during the construction of Port of Cosa on the west coast of Italy, where natural volcanic materials were used [1]. Unlike conventional concrete, which uses gravel and crushed stones as coarse aggregate, lightweight concrete utilises naturally available aggregates like lightweight expanded clay aggregate

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(LECA), palm oil clinker, shale, oil palm shale or synthetic aggregates such as expanded glass, beads, and synthetic polymer particles [2–5]. These aggregates are partially or completely used as replacements for natural coarse aggregate, resulting in lower concrete densities ranging from 800kg/m3 to 2000–2200 kg/m^3, thus making it advantageous for various engineering applications [6,7]. According to the American Concrete Institute (ACI PRC-213) [1], structural lightweight aggregate conforms to the requirements of ASTM C331/C331M [8] and has a bulk density of 880 kg/m^3 for coarse aggregate and 1120 kg/m^3 for fine aggregate. Lightweight concrete offers several advantages, including lower bulk density, improved thermal insulation, and higher energy absorption compared to normal concrete [9–12].

The LECA is one of the most used lightweight aggregates in concrete due to its enhanced alkaline corrosion and frost resistance. Although research has shown the incorporation of LECA into concrete mixes can lead to reduced mechanical properties, adding fibre has been found to compensate for the strength reduction with enhanced strength compared to normal concrete [13]. Specifically, the incorporation of polypropylene fibres LECA concrete has been reported to enhance workability and reduce crack formation, while also contributing to the overall performance [13]. Furthermore, previous studies have explored the incorporation of cementitious materials together with fibrous materials, such as fly ash plus fibre to modify the performance of expanded clay aggregate concrete for monolithic construction [14,15]. This approach has proven effective in improving mechanical properties, increasing concrete durability and reducing brittleness [16–18] with one of the studies reporting up to 65 % increase in peak load, impact energy absorption, and a consequent decrease in brittleness associated with hollow slabs [19]. However, despite its numerous advantages, lightweight concrete has its shortcomings, including lower mechanical strength [20], durability concerns due to the porous nature of the aggregate and its susceptibility to early-age cracking. Thus, efforts are ongoing to address these limitations.

For example, Lo et al. [21], investigated the effects of expanded clay aggregate properties on concrete by considering aggregate strength, w/c ratio, and porosities within the interfacial zone and the hardened concrete paste. The study found that increasing w/c results in a decrease in compressive strength and an increase in the pores within the cement paste and the aggregate/cement paste in the interfacial zone. It is also found that several studies have explored the applicability of lightweight fibre-reinforced concrete for different purposes due to its enhanced ductility [22–25]. Some of these studies have also reported up to 6 % and 14 % increases in compressive and flexural strength in lightweight concrete containing coconut shells as coarse aggregate and reinforced with Sisal fibre [26]. Similarly, another study outlined improvements in the mechanical performance of lightweight concrete containing oil palm shell aggregate as coarse aggregate and 0.75 % polypropylene fibre, in addition to 14 % improved post-failure toughness [27]. More recently, Ozkilic et al. [28], investigated the potential of coconut and sisal fibre for the enhancement of compressive and flexural properties of lightweight expanded clay concrete. Their findings revealed 8.9 % and 16.1 % improvement in compressive and flexural strength with coconut fibre and 10.1 % and 18.3 % with Sisal fibre at 2 % volume fraction. The study also recommended 20 % replacement as the optimal lightweight expanded clay content. In addition, the behaviour of LECA concrete reinforced with glass fibre has been explored. The study considered 0 %, 75 %, 85 % and 95 % LECA replacements, with varied fibre volume fractions ranging from 1 % to 2 %. It was found that a mixture containing 75 % LECA and 1 % glass fibre yielded an improvement of 14.8 % and 14.3 % in stiffness and ductility [29].

The performance of lightweight concrete is influenced by several factors such as the type of lightweight aggregate, water-cement ratio, binder characteristics, and notably the aggregate porosity which has been shown to increase energy absorption capacity [30], although with a consequent decrease in compressive and tensile strength [31]. While previous studies have investigated the mechanical characteristics of lightweight concrete containing partially replaced expanded clay aggregate, there is still limited information on fibre-reinforced concrete with coarse aggregate completely replaced with LECA. Therefore, this study aims to address this gap by completely replacing the natural coarse aggregate with lightweight expanded aggregate (LECA) in fibre-reinforced concrete containing 0 %–1.0 % polypropylene fibre. Furthermore, to address the concern of trade-off between increased energy absorption and decreased mechanical properties in the resulting LECA concrete as reported in previous studies, a constant dosage of micro silica is introduced into the concrete mix, as it reacts with the calcium hydroxide produced during cement hydration to form additional calcium silicate hydrate (C-S-H) gel within the hydrated cement particles void to enhance the particle packing.

1.1. Significance of the study

The study highlights the limitation of completely replacing natural coarse aggregate with LECA on the mechanical properties of lightweight fibre-reinforced LECA concrete. It also establishes the influence of different volume fractions of polypropylene fibre on enhancing structural performance, particularly in terms of impact energy absorption and crack resistance. The flexural performance, including first crack behaviour and flexural toughness (I_5 and I_{10}) of various concrete mixes, have been established. Furthermore, regression models for predicting impact energy absorption and crack resistance at service and ultimate loading within a 95 % confidence interval have been presented. The research also proposes optimised concrete mixes for enhanced performance at both service and ultimate loading and the correlation between these responses and flexural toughness established. The findings offer valuable guidance for the application of LECA in construction, especially related to suspended floors and other areas that might be exposed to impact loading.

2. Experimental programme

2.1. Materials

The plain lightweight concrete and fibre-reinforced lightweight concrete were produced using Grade 42.5 Ordinary Portland Cement (OPC) conforming to Malaysian Standard MS 522 [32]. Other material as illustrated in Fig. 1 includes LECA with a crushing strength of 5 MPa, density and size ranging between 620 and 720 kg/m^3 and 4–15 mm respectively.

For fine aggregate, river sand of size below 4.75 mm was used along with silica fume. Fibrillated polypropylene fibre of 19 mm in length with a specific gravity of 0.9 kg/m^3 and a tensile strength of 400 MPa was used. The superplasticiser used is Polycarboxylic Ethers named Sika Viscocrete-2192 [33].

2.2. Mix design and slab specimen production

This study adopted the LECA mix design as proposed in the LECA manual [34]. The detailed mix design of the 30 MPa concrete for the structural lightweight concrete is shown in Table 1, containing 10 % micro silica and 2.5 % super plasticiser (SP), with varying volume fractions of polypropylene fibre (PPF). The concrete density was ensured to be within 1500 kg/m^3 to 1800 kg/m$^{3.}$ LECA aggregate is highly porous; thus, it was soaked in clean tap water for an hour to ensure full saturation which can guarantee a better bond with cement paste and in turn improve the workability and strength. Thereafter the soaked LECA was air-dried using a cloth to remove trapped water.

Cylindrical specimens of 150 mm in diameter and length of 300 mm were used for the split tensile test, while the flexural test conducted rectangular prism of 150 mm × 150 mm x 500 mm according to ASTM C496 [35] and ASTM C78 [36]respectively. The slab specimens used for the impact test were produced by placing ready mix concrete into

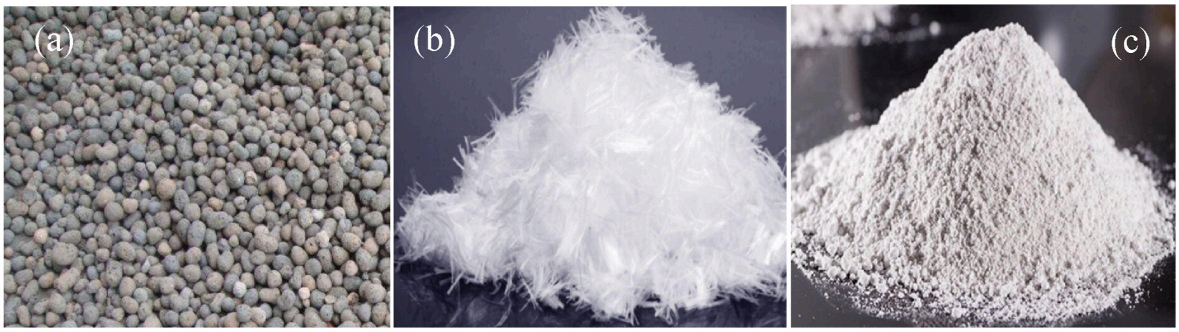

Fig. 1. (a) Lightweight Expanded Clay Aggregate (b) Polypropylene fibre (c) Silica Fume.

Table 1
Concrete mix design.

Mix Code	Cement	Sand	LECA	micro silica	W/C ratio	PPF (%)	SP (%)
	(kg/m^3)						
Control	506.19	546.69	582.12	50.62	0.36	0	2.5
CPPF-0.5 %	506.19	546.69	582.12	50.62	0.36	0.5	2.5
CPPF-0.75 %	506.19	546.69	582.12	50.62	0.36	0.75	2.5
CPPF-1.0 %	506.19	546.69	582.12	50.62	0.36	1.0	2.5

lubricated timber formwork as shown in Fig. 2 (a, b) then cured at room temperature for 24 h before being de-moulded and cured in clean water for 28 days.

2.3. Experimental programme

2.3.1. Workability and dry unit weight

The workability of each concrete mix containing varying fibre volume fractions is assessed using slump tests according to ASTM C143 [37], while the determination of the concrete dry unit weight was determined according to ASTM C138/C138M-17a [38].

2.3.2. Compressive and split tensile strength

Compressive and split tensile strength tests were conducted at the civil engineering laboratory of Universiti Tenaga Nasional, Malaysia utilising a universal testing machine according to ASTM C39 [39] and ASTM C496 [40] respectively. For each of the tests, twelve 150 mm cylindrical concrete samples were used, with three specimens to represent each concrete mix containing 0 %, 0.5 %, 0.75 % and 1.0 % respectively. During the compressive strength test, the loading was gradually applied on the damp specimen using a hydraulically operated crosshead at a rate within a range of 0.15–0.35 MPa/s. The split tensile loading was applied at a rate of within 0.01–0.03 MPa/s.

2.3.3. Flexural test

The flexural test was performed by a three-point bending test using fibre-reinforced concrete beam specimens with 150 mm × 150 mm x 500 mm dimensions according to the provision of ASTM C78 [41]. The flexural toughness of the specimens containing varying volume fractions of polypropylene fibres was determined based on the provision of ASTM C1609 [42].

The Flexural toughness of a material is the measure of energy absorption capacity or simply its ability to resist crack opening. Thus, the first-crack flexural toughness is determined by computing the area under the load-deflection curve up to the point of the first crack. Subsequent toughness indices (I_n) are determined by dividing the referenced area under the load-deflection curve by the area corresponding to the first crack deflection. In this study, indexes $I_{5\ and\ 10,}$ are considered. They are computed as ratios of the area corresponding to the 3 and 5.5 times the first crack deflection by the area under the curve up to the first crack as illustrated in Fig. 3.

2.3.4. Impact resistance

To understand the influence of polypropylene fibre content on impact resistance, energy absorption capacity and general damage mechanism of a lightweight polypropylene fibre-reinforced concrete incorporated with LECA. The low-velocity low projectile impact test based on guidance provided in the ACI 544-2R [44] Committee was adopted in this study, using square slab specimens of 300 mm × 300 mm with varying thicknesses of 20 mm, 30 mm, 40 mm and 50 mm. The aim is to analyse how each of the slab thicknesses consisting of different volume fractions of PPF reacts to impact load scenario which is lower than high-speed collisions but higher than static loading conditions. In

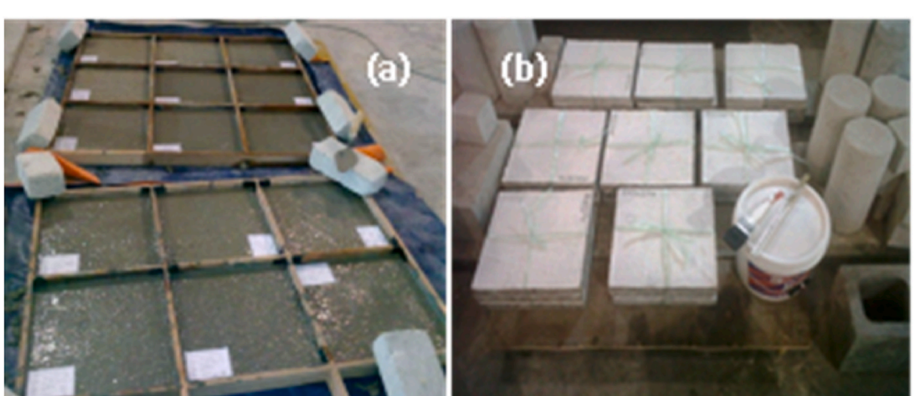

Fig. 2. Slab preparation for Impact test (a) Formwork for slab (b) slab specimens.

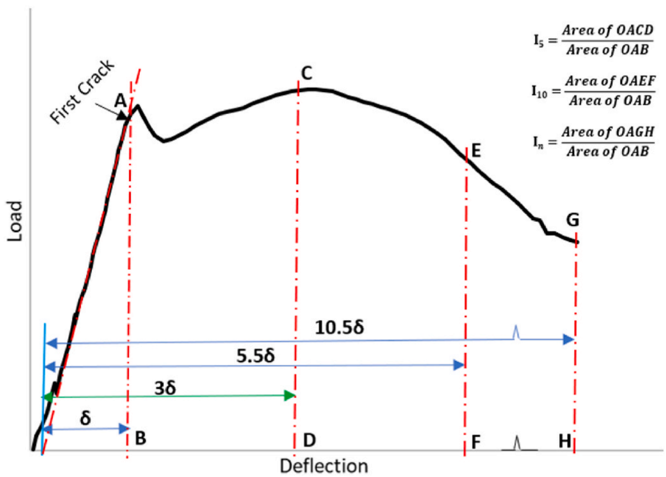

Fig. 3. Toughness index from Load-Deflection curve [43].

each case, a cylindrical steel ball is dropped from a controlled height onto a specimen simply supported to simulate a low-velocity impact scenario as shown in Fig. 4. In each case, the number of blows and drop height of the cylindrical steel ball causing service and ultimate cracks are recorded.

The service and ultimate absorption energy absorptions and crack resistance of each sample are computed using Equations (1)–(5) [44].

$$e = mgh \tag{1}$$

where, e = Energy blow (Joules), m = mass of the ball, g = 9.81 m/s^2, h = height of dropping the ball

$$EA_s = N_s{}^*e \tag{2}$$

$$EA_u = N_u{}^*e \tag{3}$$

in equations (2) and (3), EA_u is the Ultimate energy absorption, EA_s is the Service energy absorption, N_s represent the number of blows until the service crack, and N_u is the number of blows at ultimate cracks.

$$R_s = EA_s / (l_c{}^*d_s{}^*W_c) \tag{4}$$

$$R_u = EA_u / (l_c{}^*T^*W_c) \tag{5}$$

in equations (4) and (5), R_s and R_u represent Service and Ultimate crack resistance, d_s is the Maximum crack resistance, while l_c is the total length of all cracks, W_c is the Maximum crack width, and T *is* the specimen thickness.

2.3.5. *Microstructural analysis of fibre reinforced LECA concrete*

To further explore the mechanical performance of the concrete, particularly with respect to the interfacial zone, which has been identified as a significant factor influencing concrete behaviour, a Scanning Electron Microscopy (SEM) was conducted using FEI Quanta 400 high-resolution field emission scanning electron microscope as shown in Fig. 5, capable of magnification of up to 100,000. The aim was to examine the characteristics of the interfaces between LECA-cement paste and PP fibre–cement paste.

3. Prediction models and response surface analysis

Response surface methodology (RSM) is a highly effective approach widely used across various fields today. It encompasses a set of mathematical and statistical techniques used for experimental design, modelling, evaluating the impact of multiple variables, and optimisation [45]. Conventionally, this methodology relies on experimental data, but observational data as an alternative are also considered [46]. Some software used for response surface analysis includes XLSTAT, Minitab and design expert software. For this study, Version 13:2021 of Design-Expert is in this study because of the flexibility. The interactions between factors and responses are depicted in the form of contours and 3D response surfaces to illustrate the relationship.

The central composite design based on 2-factorial designs was employed for its adaptable design structure to accommodate custom models. The factors considered are the polypropylene fibre (PPF) content, and Slab thickness, while the responses include impact energy absorptions and crack resistance each at service and ultimate loading. Each slab thickness of 20 mm, 30 mm, 40 mm and 50 mm contains a varying fibre content of 0 %, 0.5 % 0.75 % and 1 % PPF. Regression models to predict responses of specimens containing up to 2 % PPF were developed. Both experimental and predicted results were analysed using ANOVA and diagnostic analysis.

Depending on the relationship between the response(s) and factors, linear, quadratic cubic, etc models are suggested as shown in equations (6) and (7).

$$f = A_0 + A_1x_i + A_2x_{ii}\ldots A_nx_n + \varphi \tag{6}$$

Where f and x represent the factor x and variable respectively. Also, A_0 is the intercept at $x_i = x_j = 0$, A is the coefficients.

Fig. 4. Illustration of low-velocity impact resistance test set-up.

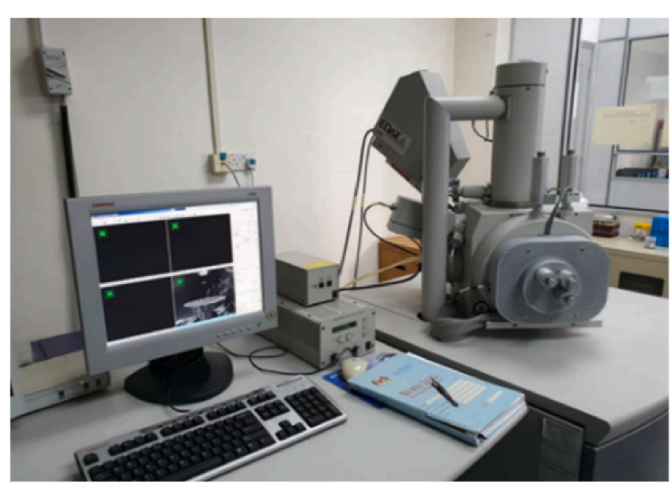

Fig. 5. FEI Quanta 400 high-resolution field emission SEM equipment.

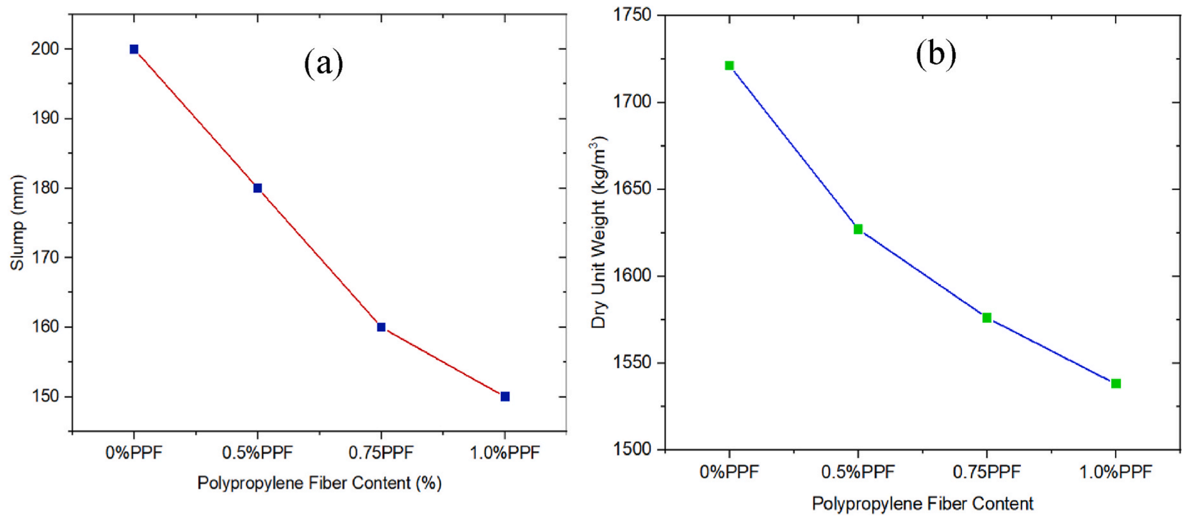

Fig. 6. Effect of PPF dosage on LECA concrete Slump and Dry Unit Weight.

$$f = A_0 + \sum_{i=1}^{n} A_i x_i + \sum_{i=1}^{n} A_{ii} x_i^{\,2} + \sum_{i=1}^{n-1} \sum_{j>1}^{n} A_{ij} x_i x_j + \varphi \tag{7}$$

Where i and j denote linear and quadratic encrypted quantities, and n is the numerical variable.

The ANOVA result of each analysis establishes the mean variability between the impact energy and crack resistance of the lightweight concrete specimens through the measure of statistical significance by ensuring a 95 % confidence level, a statistical significance of $p-\ value \leq 0.05$. In each case the $p-value$ s, *lack of fits*, *standard deviations*, and variations between adjusted and predicted coefficient of determinations $\left(R_a^2 \ and \ R_p^2\right)$ are evaluated. The R^2 measures how well the regression models can predict the response. How close the value is to 1 indicates how best the predictions are.

4. Results and discussions

4.1. Workability and dry unit weight

Fig. 6 a and b compare the variation in workability and dry unit weight in lightweight polypropylene fibre-reinforced LECA concrete. The figures show a consistent decrease of an average 10 % in workability and 3.8 % in dry unit density respectively for each 0.25 % increase in PPF content. The decrease in workability is attributed to the increased contact surface between PPF and cement matrix resulting in higher viscosity, thereby making the concrete more resistant to flow. A similar study by Abousina et al. [47] reported up to an 8.1 % reduction in workability in normal concrete, but higher reductions are anticipated in LECA. On the other hand, the reduction in density is connected to the contribution of the fibre to the overall concrete mass with the consequent increase in air void within the concrete which paradoxically caused reduced density. Similar findings have been reported by Ahmad et al. [48].(a)

4.2. Microstructural analysis of lightweight fibre-reinforced LECA concrete

Fig. 7a and b and c illustrate the microstructural analysis of the internal structure of lightweight expanded clay aggregate (LECA) in a concrete matrix.

The SEM micrograph in Fig. 7a illustrates the dense outer shell surface of the LECA with the sparsely distributed and unconnected pores. In contrast, Fig. 7b shows the internal cellular pores. The pore sizes are typically in the range of 5–50 μm, with some of the pores interconnected, thus contributing to the porosity of concrete.

Fig. 7(c.) on the other hand shows the LECA–PPF -cement paste interfacial zone (ITZ), revealing the cement paste and micro silica being chemically fused into the LECA shell bonded with PPF, sealing the internal pores perfectly. Thus, this provides an effective mechanical interlocking within the interconnected pores through the jagged shell. Combining chemical fusion and mechanical bonding allows effective force transmission between LECA and the cement matrix at the ITZ and consequently enhances strength.

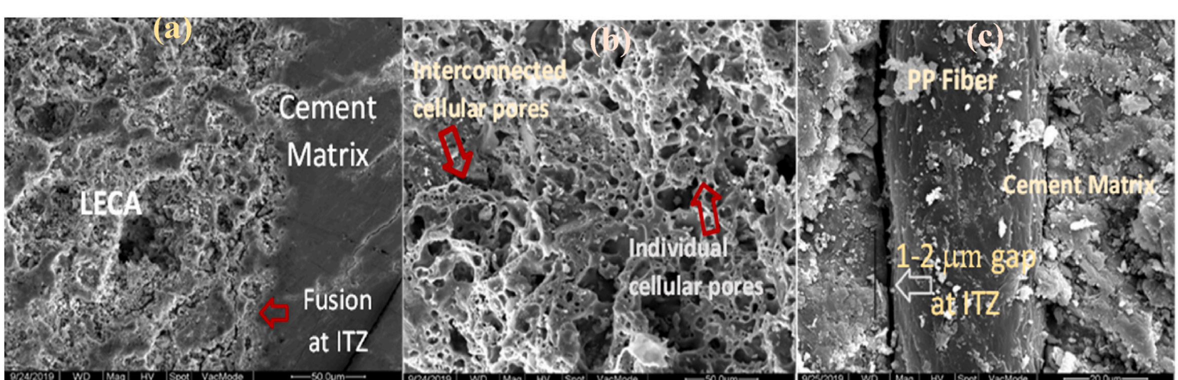

Fig. 7. SEM 500× micrographs (a) Dense outer shell surface of LECA (b) Internal cellular micropore structures (c.) LECA-PPF Cement ITZ.

4.3. Compressive and split tensile strength

Fig. 8 a and b compare the compressive and split tensile strengths of the lightweight concrete specimens with varying PPF content. A consistent decrease of 36 %–65 % in compressive strength (Fig. 8a) and up to 15 % in split tensile strength (Fig. 8b) is observed with an increase in PPF content, although with up to 23 % increase in split tensile strength at 1 % PPF. The findings contrast with the typical behaviour reported in normal fibre-reinforced concrete, where the addition of PPF usually leads to improved mechanical properties due to enhanced crack resistance. It is important to note that natural coarse aggregates typically withstand about 60 %–75 % of the compressive load of the total compressive strength of concrete [49,50]. Thus, the result infers that the complete replacement of natural aggregate with LECA could not withstand substantial compressive load due to the inherent high porosity of LECA compared to natural aggregates, thereby resulting in lower density and strength. Consequently, even with the inclusion of PPF, the overall compressive and tensile strength properties of the concrete are limited by the properties of the LECA. Furthermore, this could also be attributed to weaker bonds between the PPFs, LECA and cement matrix, resulting in weaker interfacial bonding with increasing PPF content which in turn compromises the load transfer. Most importantly, PPFs are known to be effective in controlling micro-cracks and improving ductility but do not significantly enhance load-bearing capacity. The decreasing trend in strength correlates directly with the dry unit density in Fig. 8b, indicating the need for a cautious trade-off between achieving lightweight and strength. However, this stands in contrast to the compressive strength of concrete containing normal aggregate [47,51]. Surprisingly, Yew et al. [52], reported improvement in compressive strength with concrete containing crushed LECA concrete and varying polypropylene fibre dosages, which could be due to the elimination of the void inherent in the LECA after being crushed.

4.4. Flexural performance

4.4.1. Flexural strength

The experimental flexural strength of the concrete specimens (150 x 150 x 500) as shown in Fig. 9 exhibits an irregular drop pattern in flexural strengths ranging from between 4 % and 120 % with variation in volume fractions of PPF. The maximum drop was observed at 0.75 % PPF but with subsequent improvement of up to 90 % when the PPF content is increased from 0.75 % to 1.0 %. However, the flexural strengths exhibited by all the samples containing PPF are lower than the control sample.

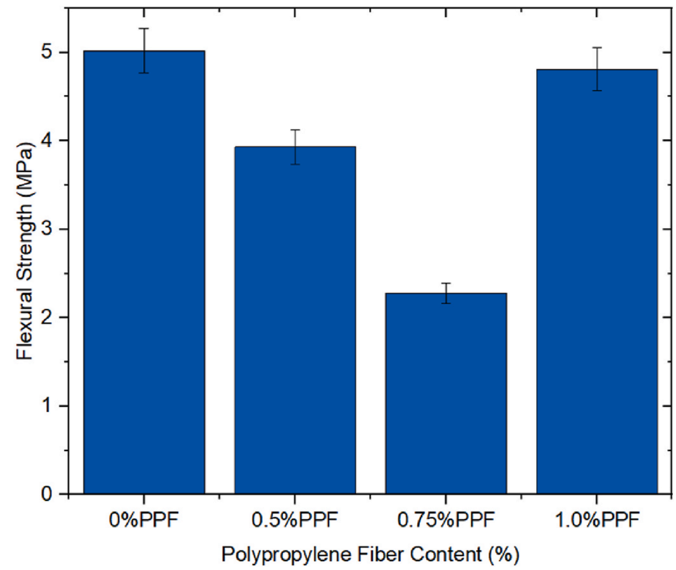

Fig. 9. Variation of flexural strength of concrete with varying polypropylene content.

Fig. 10 compares the load-displacement curves of the lightweight fibre-reinforced-LECA concrete specimens. The control sample (0%PPF) failed outrightly upon attaining the flexural ultimate strength, despite being able to withstand the maximum flexural load. The pre-failure behaviour is characterised by a steady stiff curve and a low rate of change in deflection showing the high stiffness of the specimen. Thus, the post-failure behaviour exhibited is attributed to the specimen's inability to withstand loading beyond the mortar matrix cohesion bond force, resulting in a rapid increase in loading with the corresponding deflection in a linear pattern. This is followed by the manifestation of obvious cracks and a sudden rupture upon reaching peak load. This behaviour was also observed during the experimental test, with the specimen crushing explosively due to low ductile performance.

In contrast, the flexural performance has shown varying degrees of enhancement with increased PPF content. This is attributed to the increased ability of the specimens containing fibre to continue to withstand significant flexural loads even at deflections beyond the

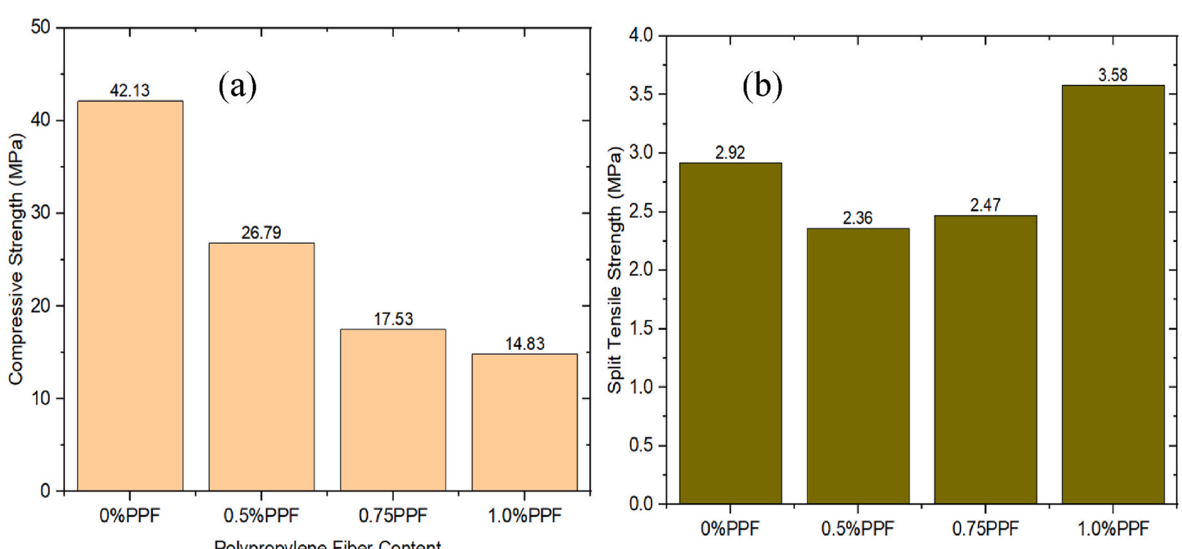

Fig. 8. Variation in (a) compressive strength and (b) Split tensile strength with different polypropylene fibre content.

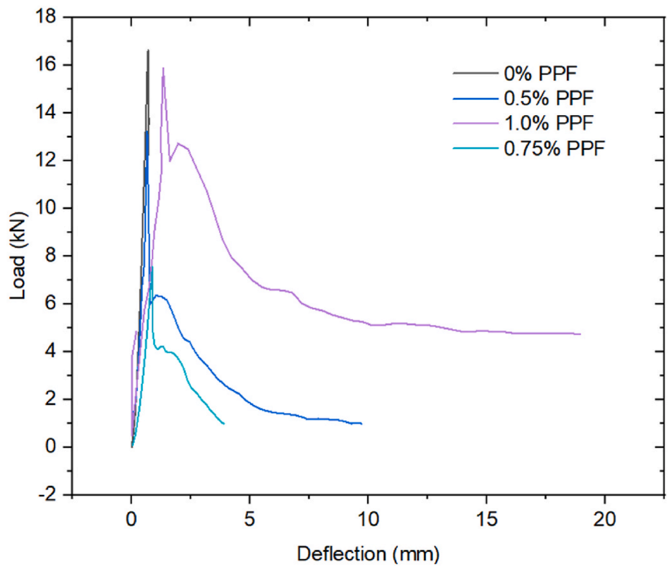

Fig. 10. Variation in Load deflection characteristics of lightweight concrete with varying fibre content.

fracture point of plain concrete. All samples containing PPF exhibit increased work of fracture even after reaching ultimate strength and the consequent manifestation of obvious cracks. This is due to the combination of the mortar matrix cohesion bond and fibre anchoring force. As the deflection increases, the load on each specimen gradually decreases towards stability. Thus, the sample containing 1.0%PPF can be said to have better ductile performance at almost the same peak load as the control sample, with about 180 % enhanced crack formation resistance and only a 5 % decrease in flexural ultimate strength. Furthermore, Improvement of 87 % and 28 % in deflection resistance in samples with 0.5%PPF and 0.75%PPF is observed with a reduction of about 26 % and 112 % in ultimate strength, respectively. Thus, it can be inferred, that higher PPF content is required for enhanced load-deflection performance of the studied concrete. Several studies have reported similar findings at different PPF volume fractions [52,53].

4.4.2. *First crack flexural deflection, strength, and flexural toughness*

The first crack flexural deflection is an important parameter for assessing the structural integrity and performance of concrete or other materials in flexural applications. It refers to the displacement of a structure at a point when the load increases beyond the first crack load, at which point the cracks propagate further. The first crack load refers to flexural loading at which the material begins to fail locally through the development of cracks.

Hence, the first crack deflections of the beam specimens with and without fibre are compared in Fig. 11 (a). The result shows an increase of 24 % and 90 % with 0.75 % and 1.0 % fibre content. This improvement infers lower stiffness and greater ductility at 1.0 % fibre content. Meaning the specimen can accommodate minor cracks without significant loss of load-carrying capacity. Thus, specimens with higher first crack deflection are safer, since they can provide warning cracks before reaching critical failure. The first crack flexural strength as shown in

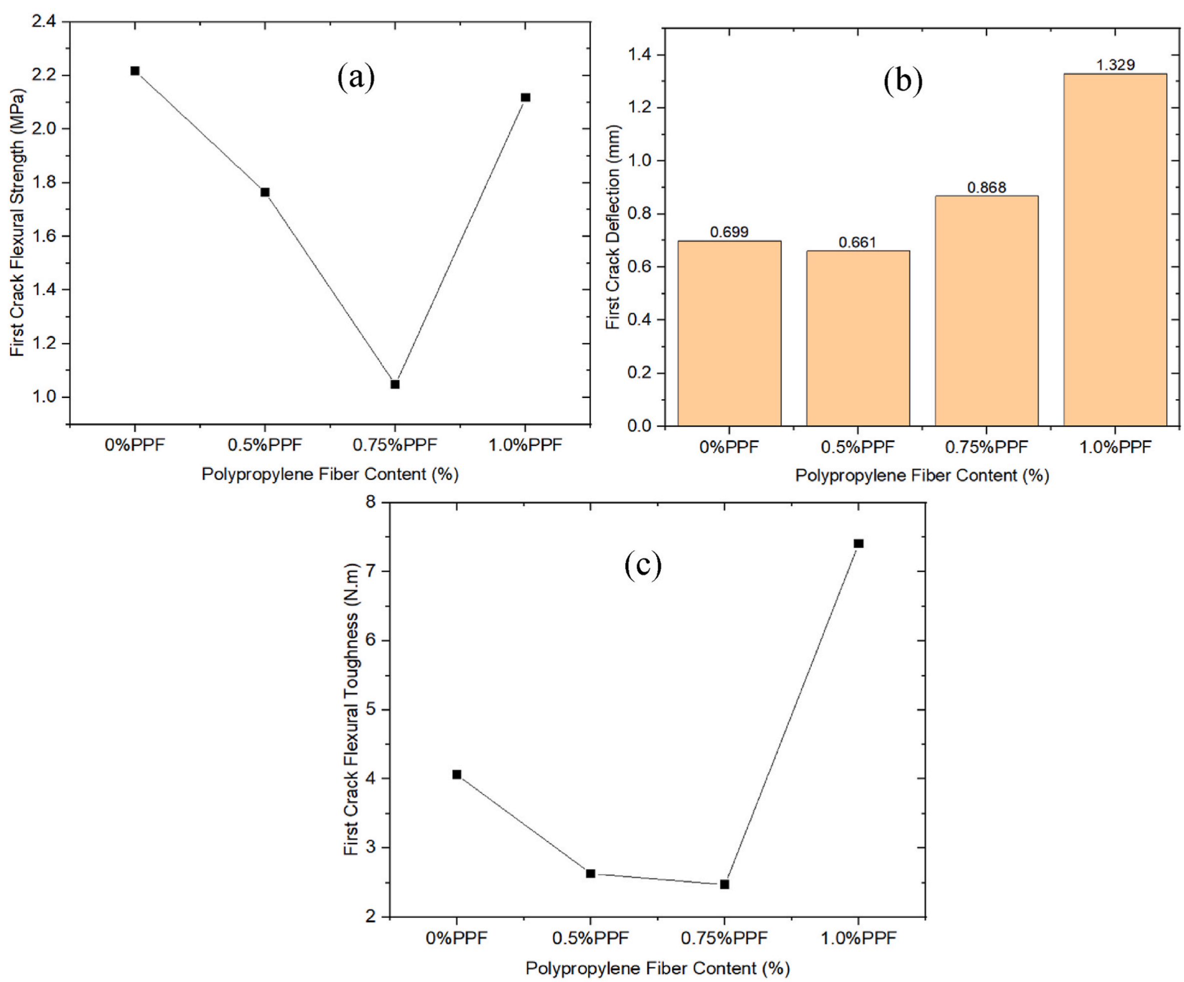

Fig. 11. Variation of (a) first crack strength, (b) deflection and (c) Toughness with varying polypropylene fibre content.

Fig. 11b characterizes the behaviour of the specimens up to the onset of crack manifestation in the concrete matrix. It represents stress exerted by the load corresponding to the first crack using the modulus of rupture relation. The values can be seen to decrease in direct proportion with 0.5 % and 0.75 % fibre content followed by a subsequent increase in specimen containing 1 % polypropylene fibre (PPF) content although slightly lower when compared to the control sample which calls for the need to explore PPF beyond 1.0 % for further insight into this relationship. The result reveals that the high PPF might improve the initial response of the bean specimens before cracking occurs. Generally, the introduction of PPF enhances crack resistance in concrete [54]. Furthermore, the incorporation of other pozzolanic materials lime micro silica has been reported to enhance general strength and durability [55].

On the other hand, Fig. 11(c.) compares the first crack toughness of the specimen. This represents the energy equivalent to the area under the load-deflection curve up to the first crack deflection [56]. The trend indicates a similar pattern with the first crack flexural strength but with a significant 69.2 % improvement exhibited in specimens containing 1 % fibre content compared to the control sample. The result infers the ability of the concrete to sustain loads beyond the initial cracking stage with an increase in PPF content greater than 0.75 %.

4.4.3. *Flexural toughness indices and residual strength*

The flexural toughness indices of the specimens are determined to assess the concrete capacity to withstand flexural load while exhibiting adequate ductility and energy absorption even after initial cracking occurs. Fig. 12a indicates significant improvements in both I_5 and I_{10} toughness indices with increasing fibre content. Up to a maximum of about 300 % and 570 % improvement was exhibited in specimens containing 1 % compared to the control sample. A similar pattern was observed in the residual strength factor with enhancement of 55.4 % compared to the control sample as shown in Fig. 12b. The improvement in toughness indices infers that introducing polypropylene fibre into the mix has increased the specimen bending resistance and rigidity, thus increasing residual strength. Similar findings are reported in previous studies [55].

4.5. *Impact and crack analysis*

To proportionately access the impact and crack resistance performances of the lightweight concrete, the weight of the cylindrical ball and height of fall were varied based on fibre content and slab thickness. A cylindrical ball of 0.509 kg with a falling height of 0.5m was used for samples without PPF, while a cylindrical ball of 1.05 kg was used for samples containing PPF, a varied height of fall of 0.48m, 0.58m and 0.68m was used for fibre contents, 0.5 %, 0.75 % and 1.0 % respectively. This allows for a proportionate scenario regarding impact and potential energy with varying slab thicknesses and fibre content.

4.5.1. *Crack and failure pattern of the lightweight fibre reinforced-LECA concrete slabs*

Fig. 13 illustrates specimens' crack and failure patterns at an ultimate number of blows (N_u). The increasing N_u across the row and down the column indicates a general enhancement in impact resistance with both increases in slab thickness and fibre content. The maximum number of blows (200) is exhibited by the 50 mm specimen containing 1.0 % content, which is about 6 times higher than the 50 mm specimen with 0 % PPF. Even at this higher number of blows, the crack manifestation does not appear to have caused complete segmental failure on the distal faces. This is attributed to the combined solidification of the concrete matrix resulting from the reaction of silica fume and LECA, in addition to the efficient bridging mechanism at the crack points by the PPF. The number of blows at the appearance of the first crack (i.e. at service) and at failure (at ultimate) were used in the subsequent section for the computation of impact energy absorption of the specimens. Previous studies have reported general improvement in crack resistance of fibre-reinforced concrete, which was attributed to the high tensile strength of the fibre and its ability to bridge between crack openings [55,57,58].

4.5.2. *Impact energy absorption*

4.5.2.1. Experimental results. Fig. 14 (a) and (b) illustrate the experimental impact energy absorptions of lightweight fibre-reinforced LECA slab specimens under service and ultimate impact load respectively. In each case, the 2D contour plot demonstrates the factors' correlational influence on the concrete impact energy absorption performance. A general improvement is observed with increased polypropylene fibre (PPF) content. Specifically, a 50 mm specimen containing 1.0 % PPF exhibited maximum service and ultimate impact energy absorption of 445.24 J and 1370 J, respectively. This represents a 30- and 23-times improvement compared to the control sample with the same fibre content. The improvement observed in the ultimate performance indicates the sustained resilience of the specimens due to the continued absorption of extreme impact loading. Under service loading, the contour plot indicates no significant influence with up to 38 mm slab thickness containing up to 0.8 % PPF. However, under ultimate loading, a strong correlational influence is evident from the 44 mm slab thickness with all doses of PPF, which increases with higher PPF content. This increase is

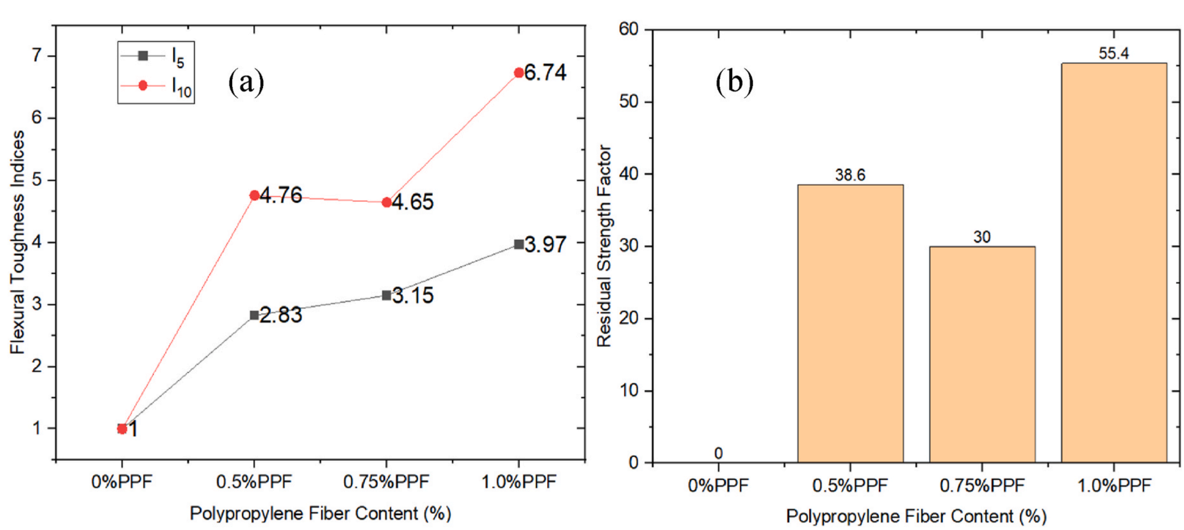

Fig. 12. Variation of (a) flexural toughness indices (b) residual strength factor.

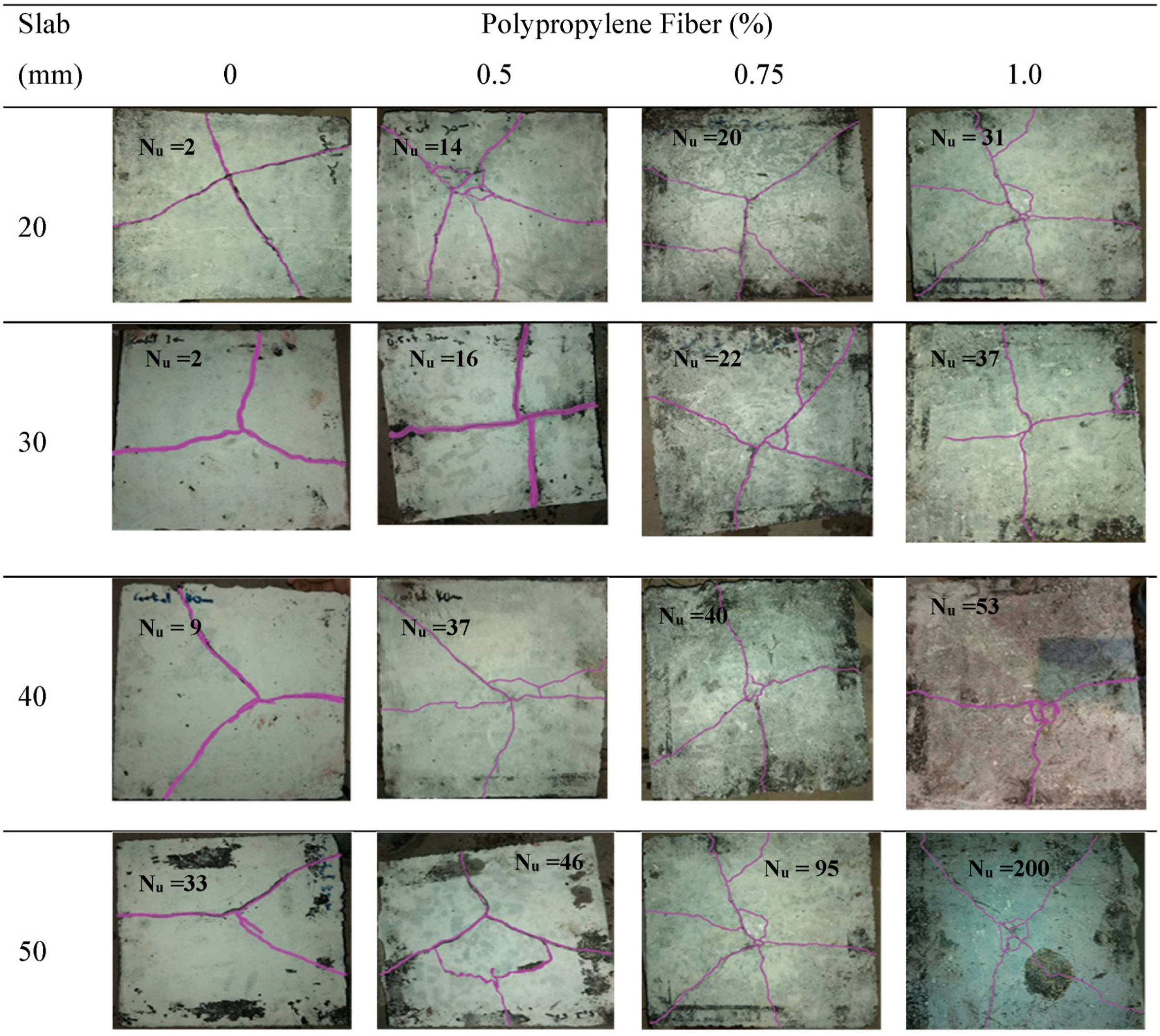

Fig. 13. Illustration of crack patterns of slab specimens with varying thickness and fibre content.

demonstrated by the gradual change in contour from blue to turquoise-green and yellow.

The recorded improvement is attributed to the contribution of several factors including adequate fusion of LECA and consequent densification of the microstructure resulting from extra C-H-S from micro-silica and fibre length. A-Rousan and Alhassan [59] reported similar improvements in impact resistance of two-way slabs containing 0.9 % polypropylene fibre. Other studies, including Yoo et al. [60], and Ja'e [57,58] also reported similar improvements with steel and basalt fibre respectively. The inclusion of up to 10 % silica fume in concrete has also been reported to influence higher compressive, tensile and flexural strength in LECA concrete [61].

4.5.2.2. Predicted result. To further explore the impact of the energy absorption performance of the lightweight concrete, additional responses were predicted using regression models developed from the experimental results using design expert software. The predicted responses as detailed in Table 2 were derived using experimentally designed factors and computed using Equations (8) and (9).

$$EA_s = 386.37 - 342.24A - 25.34B + 8.19AB + 162.1A^2 + 0.40B^2 \quad (8)$$

$$EA_u = 1108.72 - 1267.43A - 67.41B + 33.05AB + 536.95A^2 + 0.96B^2 \quad (9)$$

where A and B are the polypropylene fibre content and slab thickness respectively. The model validation using ANOVA revealed that all components of the models were significant, with p-values >0.5 and the difference between the predicted and adjusted coefficient of determination (R^2) is < 0.2. Furthermore, the diagnostics analysis of the responses is also adequate.

The predicted responses illustrated in contour plots Fig. 15 (a and b) show a significant 104 % and 112 % improvement in the impact energy with 2 % PPF. This is evident by the change in colour from yellow to reddish as compared to the experimental plot. Furthermore, an increase in fibre dosage with corresponding thickness significantly improves the impact energy absorption of concrete. Additionally, the response surface results provide a wider option for varying relationships and influence of the lightweight polypropylene fibre-reinforced LECA concrete. Thus, PPF content between 1 % and 2 % is considered adequate for enhanced impact energy absorption under both service and ultimate loading.

4.5.3. Crack resistance performance

4.5.3.1. Experimental results. Fig. 16 a and b show variations in crack resistance with slab thickness and fibre content under service and ultimate impact loading. Significant enhancement in the crack resistance is observed with an increase in both slab thickness and fibre content with maximum crack resistance of 1746 MPa and 4455 MPa exhibited at

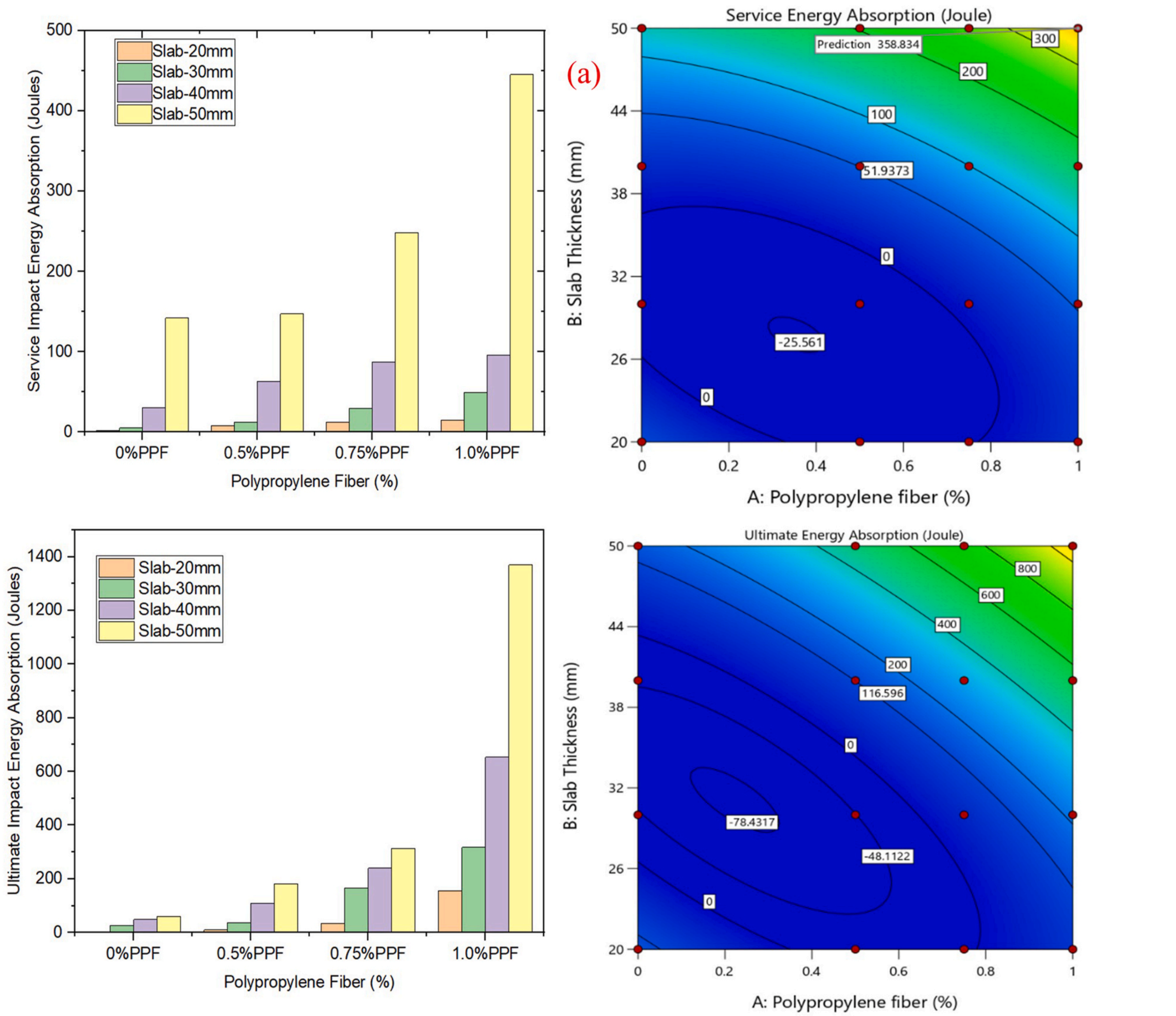

Fig. 14. (a) Service impact energy absorption variation (b) 2D Contour Plot showing the influence of fibre content and slab thickness on service impact energy absorption.

Table 2
Predicted service (EA_s) and ultimate (EA_u) impact energy absorptions.

Run	PPF (%)	Slab Thickness (mm)	EA_s (Joules)	EA_u (Joules)
1	1.25	40	254.26	863.37
2	1.25	30	122.46	448.91
3	1.50	35	275.82	973.48
4	1.50	20	138.30	444.96
5	1.00	35	100.96	357.67
6	2.00	50	912.49	3068.35
7	1.25	40	254.26	863.37
8	0.50	45	117.92	273.43
9	2.00	20	332.77	1081.39
10	2.00	50	912.49	3068.35
11	1.50	35	275.82	973.48
12	0.50	50	203.61	477.34
13	1.00	35	100.96	357.67
14	1.00	50	358.85	1072.54
15	1.25	30	122.46	448.91
16	1.50	50	595.14	1936.21

service and ultimate stage by a 50 mm slab specimen containing 1 % fibre content. This is about 17 times and 15 times higher than the control samples. The 2D contour plot of the ultimate impact energy absorption highlights a varying correlation with different thicknesses and PPF. This enhanced crack resistance is attributed to the combined stress distribution and reduced risk of localised failure due to the increased thickness and load-bearing capacity resulting from the bridging effect of the fibres in the crack sites due to high tensile stress properties. Liang et al. [62], reported polypropylene fibre as having a superior inhibitory effect on the initiation and propagation of cracks in concrete. Results in Ref. [63], also indicated a reduction in crack resistance with increasing fibre length. The enhanced crack resistance is attributed to the combined stress distribution and reduced risk of localised failure due to the increased thickness and load-bearing capacity resulting from the bridging effect of the fibres in the crack sites due to high tensile stress properties. Liang et al. [62], reported polypropylene fibre as having a superior inhibitory effect on the initiation and propagation of cracks in concrete. Results in Ref. [63], also indicated a reduction in crack resistance with increasing fibre length.

4.5.3.2. Predicted results. Regression models developed to predict crack resistance of varying slab thicknesses containing different polypropylene fibre content are presented in Equations (10) and (11). Where A and B are the polypropylene fibre content and slab thickness respectively. The validation of the models using ANOVA revealed that all

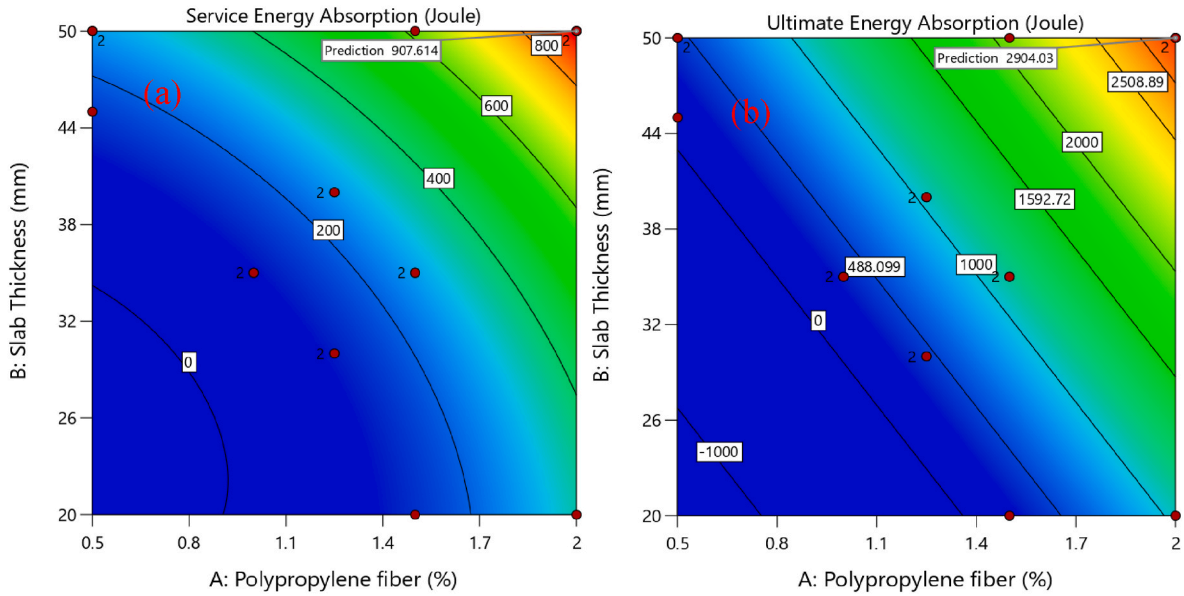

Fig. 15. Predicted correlational influence of slab thickness and polypropylene fibre on Impact energy absorption: (a) under service loading (b) under ultimate loading.

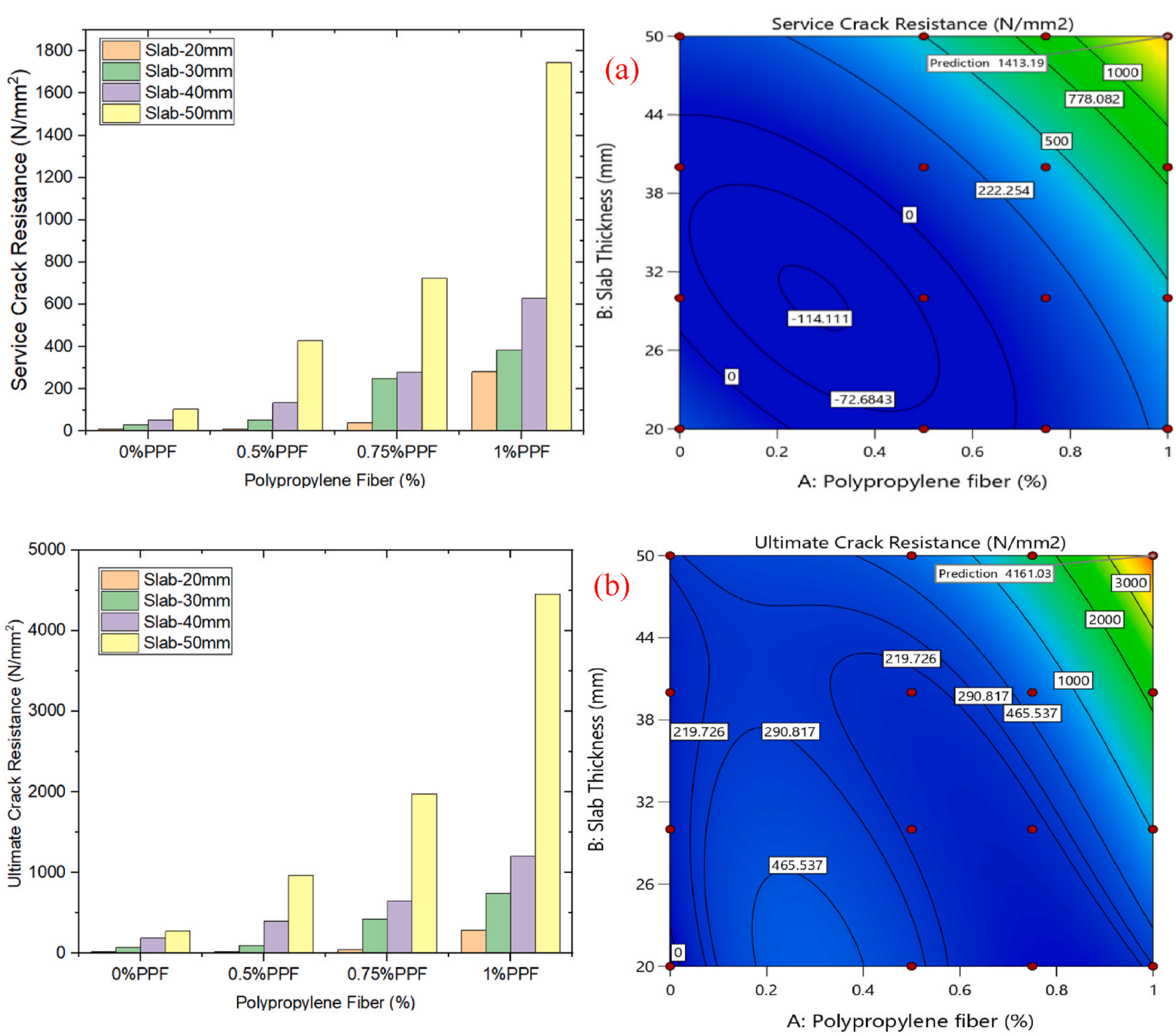

Fig. 16. Experimental crack resistance of lightweight fibre-reinforced concrete slabs (a) Service crack resistance (b) Ultimate crack resistance.

components of the models were significant, with p-values >0.5 and the difference between the predicted and adjusted coefficient of determination (R^2) is < 0.2. Furthermore, the diagnostics analysis of the responses is also adequate.

$$R_s = 1156.47 - 1793.48A - 68.43B + 39.57AB + 1097.88A^2 + 0.96B^2 \tag{10}$$

$$R_u = -2403.96 + 10789.87A + 212.22B - 347.81AB - 17088.24A^2 - 5.96B^2 + 243.21A^2B + 3.17AB^2 + 7506.747A^3 + 0.06B^3 \tag{11}$$

The predicted crack resistance of slab specimens containing between 0.5 % and 2 % polypropylene fibre content is demonstrated in the contour plots shown in Fig. 17a, b. The aim is to extend the findings revealed by the experimental results to allow for a reasonable conclusion. Fig. 17a indicates a general increase in crack resistance with higher PPF dosage. With 4627 N/mm^2 maximum crack resistance reached by a 50 mm slab containing 2 % PPF.

On the other hand, the ultimate crack resistance demonstrated a significant improvement with PPF from 1.4 % up to 2 % exhibiting up to a maximum of 32711N/mm^2 as shown in Fig. 17b. Thus, this PPF range is considered optimum. Table 3 illustrates the detailed predicted responses.

4.6. Optimisation of impact energy absorption and crack resistance

Fig. 18 (a and b) demonstrate optimisation plots of ultimate Impact energy absorption and crack resistance. The yellow region in the response overlays specifically highlights areas where optimal responses can be achieved with a 95 % confidence interval (CI). As depicted in Fig. 18a, the yellow region represents ultimate impact energy absorption between 273.43 J and 3068.35 J, while Fig. 18b illustrates the range of ultimate crack resistance between 1353.2 MPa–32843.5 MPa. Furthermore, Fig. 18 (c) demonstrates regions where combined optimised responses can be achieved. It is evident that a 47 mm concrete specimen containing 1.73 % PPF yields optimal impact energy absorption and crack resistance at service and ultimate loading of up to 680 J, 2384 J, 3823 MPa and 16279 MPa, respectively, which is equivalent to 4.8, 15.2, 37, and 56 times, respectively.

Table 3
Predicted crack resistance at service (R_s) and ultimate (R_u) loading.

Run	PPF (%)	Slab Thickness, (mm)	R_s (N/mm^2)	R_u (N/mm^2)
1	1.25	40	1404.39	−2571.36
2	1.25	30	923.37	−2682.11
3	1.50	35	1792.59	2679.46
4	1.50	20	1138.25	1353.20
5	1.00	35	624.50	−5678.74
6	2.00	50	4891.88	32843.50
7	1.25	40	1404.39	−2572.36
8	0.50	45	285.393	−9015.16
9	2.00	20	2558.50	17230.60
10	2.00	50	4891.88	32843.50
11	1.50	35	1792.59	2679.46
12	0.50	50	497.27	−9777.13
13	1.00	35	624.50	−5678.74
14	1.00	50	497.27	−9777.13
15	1.25	30	923.37	−2682.11

4.7. Correlation analysis of impact energy absorption and crack resistance with flexural toughness

4.7.1. Correlational relationship of impact energy absorption with flexural toughness

Concrete toughness refers to the energy equivalent to the area under the load-deflection curve up to a specified deflection. This section correlates the concrete specimens' I_5 and I_{10} toughness indices containing 0 %, 0.5 %, 0.75 % and 1.0 % polypropylene fibre with the corresponding impact energy absorption. Fig. 19a show the regression analysis of flexural toughness (I_5) and impact energy absorption, while Fig. 19b illustrates a comparison with the I_{10} analysis. The figures indicate a strong correlation between flexural toughness and impact energy absorption, with significant improvement with increased toughness as shown in the previous section. It is important to note that each toughness is a function of polypropylene fibre volume fraction of 0 %, 0.5 %, 0.75 % and 1.0 % respectively. The model fit captures the overall specimen performance, emphasising the strong dependence of the properties with each parameter. Generally, the overall correlation is accurate, with the coefficient of determination (R^2) for all the regression models being closer to 1 and Pearson's coefficient of correlation (r.) >0.5. Thus, further prediction can be made from the models with a 95 % confidence interval.

The figures further infer the performance capability of the

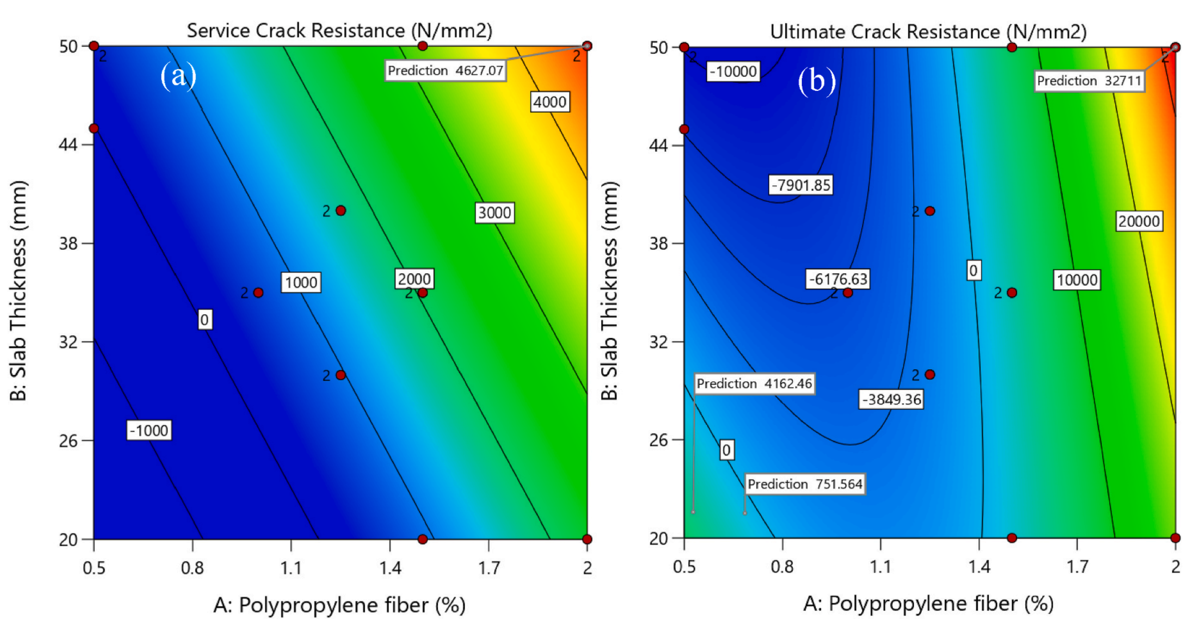

Fig. 17. Predicted crack resistance of lightweight fibre-reinforced concrete slabs (a) Service crack resistance (b) Ultimate crack resistance.

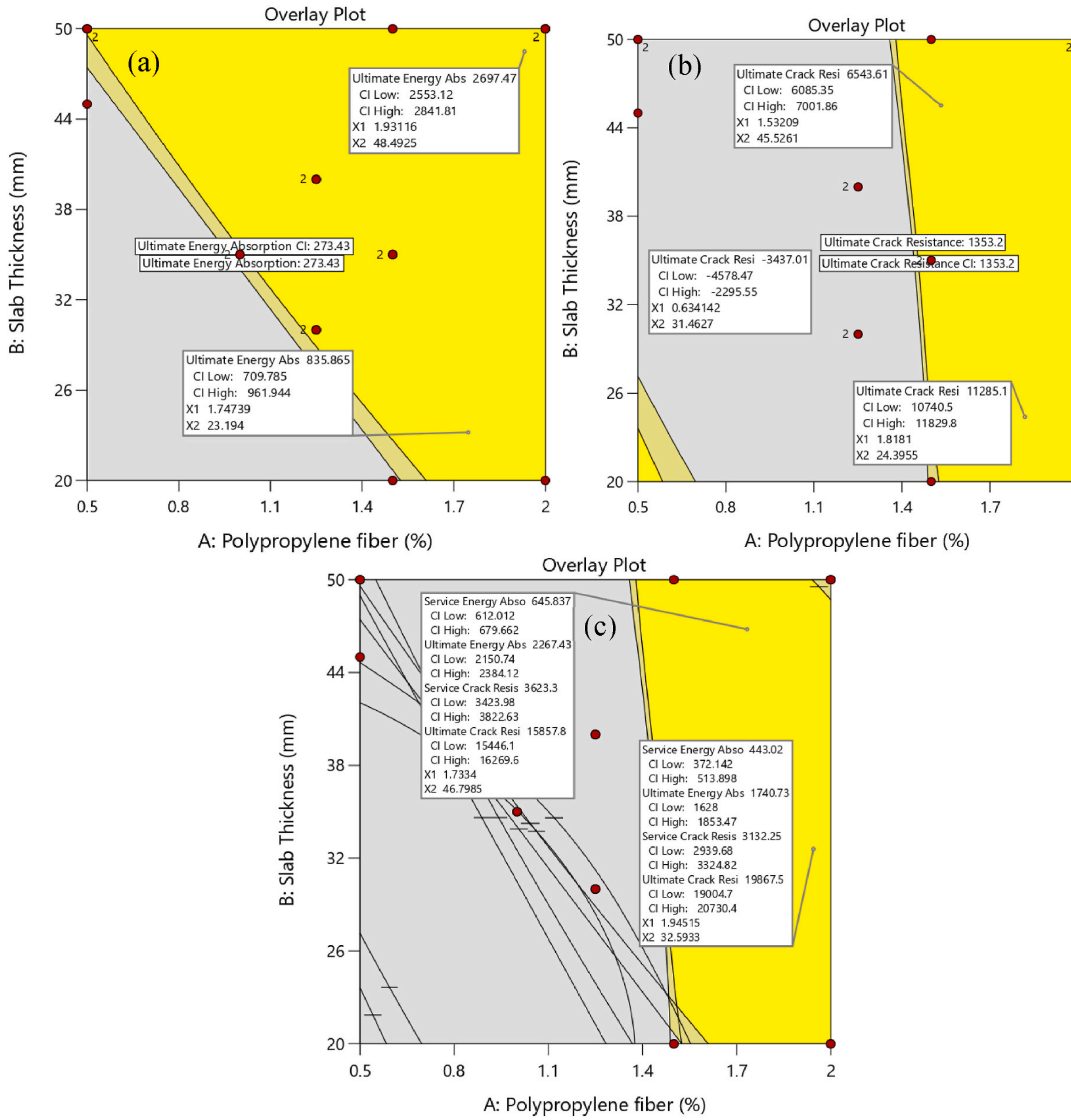

Fig. 18. Optimised responses: (a) ultimate impact energy absorption (b) ultimate crack resistance (c) Combined responses for service and ultimate loading.

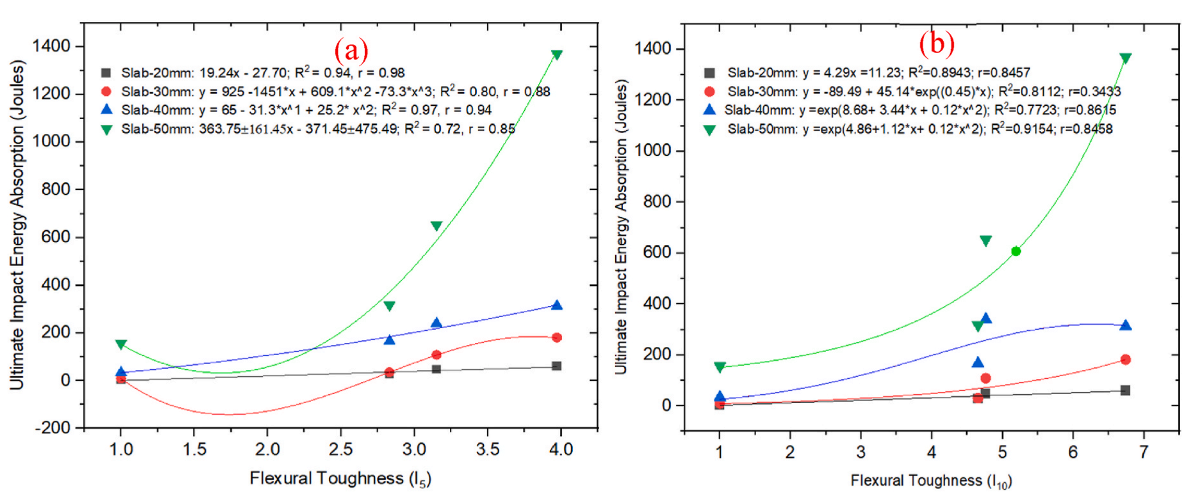

Fig. 19. Regression correlation plots of ultimate impact energy absorption with flexural toughness indices (a) E_u and I_5 (b) E_u and I_{10}.

lightweight concrete to withstand deflections up to 5.5 times the first crack deflection thereby indicating enhanced impact and bending performance which is an important parameter in structural elements like beams, slabs and pavements. Similar studies reported similar trends using different fibres, for example, Sonar and Sathe [64] reported efficient energy absorption, toughness, and strength, as well as adequate steel fibre distribution and increased slab thickness. Other studies have reported similar correlations between energy absorption and toughness of LECA concrete as related to the enhanced load-carrying capacity of the concrete [65,66].

4.7.2. Correlation analysis of crack resistance and flexural toughness

Fig. 20a illustrates the correlation between ultimate crack resistance with flexural toughness (I_5), while Fig. 20b compares the crack resistance with I_{10}. These correlations are important as they highlight the relationship between the crack resistance capabilities of the proposed concrete and the toughness indices. The toughness is determined from the area under the load-deflection curve with respect to a particular deflection of interest. In this case, toughness indices I_5, and I_{10} are considered with reference based on the guidance in ASTM C1018 [43]. The figures explicitly reveal a strong correlation between the crack resistance at all flexural toughness indices considered which are derived from specimens containing 0 %, 0.5 %, 0.75 % and 1.0 % respectively. These relationships are emphasised by the coefficient of determination (R^2), and Pierson's correlation coefficient (r-) on each figure. In each case, R^2 and are closer to 1 and greater than 0.5 respectively. Previous studies have reported similar performance in general fibre-reinforced concretes [66].

These correlations are attributed to several factors, particularly the interplay between fibre bridging, enhanced energy absorption, fibre characteristics and the development of multiple cracking behaviours. The crack resistance of the specimen can be seen to increase with the increase in the flexural toughness which is in direct proportion with the fibre content. This infers improvement in both toughness and improved crack resistance. The lightweight concrete specimens also had 1.0 flexural toughness, which indicates the failure of the specimens at the first crack. On The other hand, all specimens with higher toughness can transfer stresses from one side of the crack to the other, thereby effectively resisting further crack propagation. Thus, exhibiting the resilient performance of absorbing more deformation as illustrated in section 4.5.1 which in turn prevents sudden failure of the specimen. Furthermore, this correlation is a clear indication of the specimen's ability to gradually accommodate additional microcracks and maintain load-carrying capacity which in turn contributes to the enhanced crack resistance.

Based on the findings presented, which include advantages and disadvantages of the specific structural performance of the lightweight fibre-reinforced LECA concrete, a range of concrete mix and slab thicknesses can be adapted for specific intended applications. This is especially relevant due to the optimised predicted outcomes on impact energy absorption and crack resistance, and their correlation with flexural toughness.

5. Conclusion

The structural performance of lightweight polypropylene fibre-reinforced LECA concrete has been investigated. Several concrete mixes containing 0 %, 0.5 %, 0.75 % and 1.0 % polypropylene fibre (PPF) content have been considered. The natural aggregate has been completely replaced with the LECA in each case. The concrete properties including mechanical properties, impact energy absorption and crack resistance have been explored using experimental and response surface analysis.

- The regression models developed have successfully predicted Impact energy absorption and crack resistance of the lightweight fibre-reinforced LECA concrete slabs with varying thickness and polypropylene fibre within a 95 % confidence interval and p-values less than 0.05.
- Improvement of up to 300 % and 570 % in flexural toughness I_5 and I_{10} is achieved with 1 % polypropylene fibre, with consequent 55.4 % residual strength. This indicates the concrete's ability to withstand flexural load while exhibiting adequate ductility, bending resistance, rigidity and energy absorption even after initial cracking.
- An optimised ultimate impact energy absorption of 2841 J was achieved with a 47 mm slab thickness containing 1.5 % PPF content within a 95 % confidence interval, representing a 10-fold improvement compared to a 50 mm slab of normal LECA concrete.
- Additionally, optimised ultimate crack resistance of 7002 N/mm^2 was achieved with a 45 mm slab containing 1.5 % PPF at a 95 % confidence interval, representing a 25 times improvement compared to 50 mm normal LECA concrete.
- A combined optimised ultimate crack resistance and impact energy absorption of 16270 N/mm^2 and 2384 J was achieved with a 47 mm slab thickness containing 1.73 % PPF at a 95 % confidence interval.
- Up to 23 % improvement in split tensile strength was achieved with 1 % polypropylene fibre.
- With 1 % polypropylene fibre, up to 180 % improvement in the concrete ability to withstand loading beyond the fracture point due to enhanced mortar matrix cohesion and fibre anchoring force.

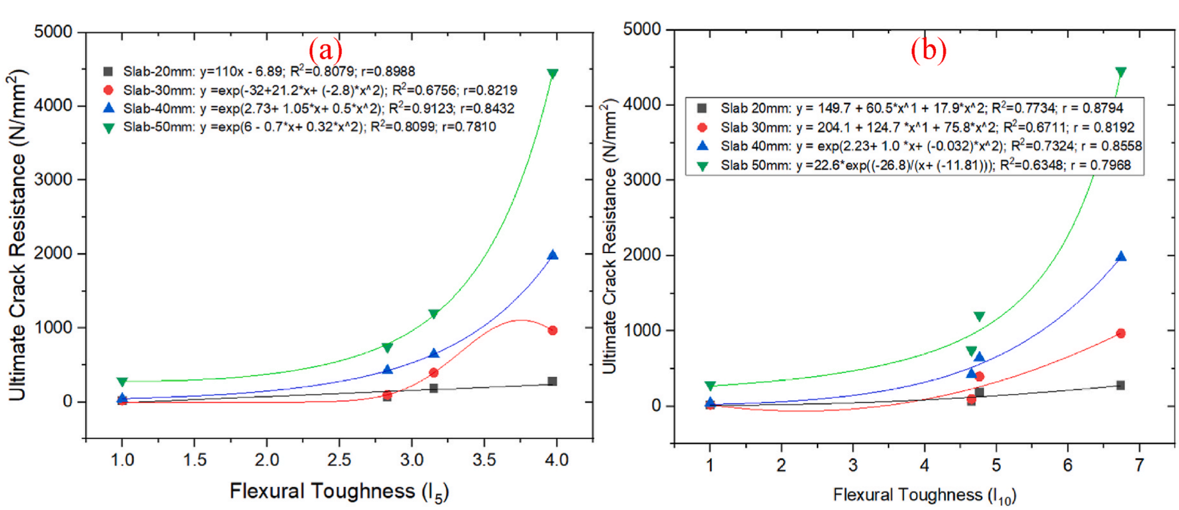

Fig. 20. Regression correlation plots of service (R_s) and ultimate (R_u) crack resistance and flexural toughness (a) R_s and I_5 (b) R_u and I_5 (c.) R_s and I_{10} (d) R_u and I_{10}.

– 90 % improvement in first crack deflection and 69.2 % in flexural toughness with 1 % fibre content. That is the ability to accommodate minor cracks without significant loss of load-carrying capacity.
– A strong correlation is established between the flexural toughness and the impact energy absorption.

CRediT authorship contribution statement

Idris Ahmed Ja'e: Writing – Original draft, Visualization, Investigation, Formal analysis, Writing – review & editing, Software, Validation, Data Curation. **Zakaria Che Muda:** Writing – original draft, Visualization, Supervision, Project administration, Formal analysis, Data curation, Conceptualization. **Mugahed Amran:** Writing – review & editing, Visualization, Validation, Funding acquisition. **Agusril Syamsir:** Writing – review & editing, Supervision, Project administration. **Chiemela Victor Amaechi:** Writing – review & editing, Validation, Software, Data curation. **Ebrahim Hamid Hussein Al-Qadami:** Writing – review & editing, Software, Data curation. **Marco Antonio Díaz Huenchuan:** Writing – review & editing, Visualization, Resources. **Siva Avudaiappan:** Writing – review & editing, Visualization, Resources, Funding acquisition, Data curation.

Declaration of competing interest

The authors 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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