ENHANCING MECHANICAL BEHAVIOUR OF LIGHTWEIGHT FOAMED COMPOSITE USING PALM OIL EMPTY FRUIT BUNCH FIBRE

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Abstract

The inclusion of Palm-oil Empty Fruit Bunch Fibre (PEFBF) into Lightweight Foamed Composite (LFC) presents a viable sustainable material by reducing cement and sand usage, replacing it with foam and natural fibre. This approach achieves both waste utilisation and material conservation, while conserving LFC's inherent lightweight and functional properties. By incorporating 1.25% volume fraction of PEFBF into LFC at a density of 1300 ± 50 kg/m³, mechanical analysis up to 90-days was conducted through compression, splitting tensile and flexural test. Scanning Electron Microscopy-Energy Dispersive X-ray spectrometry (SEM-EDX) analysis was conducted to examine the microstructural bonding and chemical composition. Results indicated that LFC-PEFBF required a higher water-cement ratio to prevent fibre agglomeration, as the inclusion of PEFBF tended to reduce the LFCs consistency and flowability. Moreover, LFC-PEFBF compressive strength showed modest increment, while splitting tensile and flexural strength demonstrated significant increases of up to 16% and 9%, respectively. A performance index evaluation confirmed the positive impact of PEFBF on LFC's mechanical properties under same densities. SEM-EDX analysis revealed that PEFBF's higher surface roughness, improved fibre-matrix bonding, and effective stress-transfer contributed to the enhanced mechanical behaviour after 56 days of curing. These findings suggest that LFC-PEFBF offers a viable and sustainable solution for civil construction applications, promoting innovative and environmentally friendly building practices.

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1.0 INTRODUCTION

The ever-growing demand for construction materials coupled with the depletion of natural resources and environmental concerns is pushing the boundaries of innovative civil construction material in the construction industry. For Lightweight Foamed Concrete (LFC), the material utilises cellular technology which replace portion of cement and sand with foam, significantly contributing to environmental impact control for the industry. Likewise, LFC offers several practical and economic advantages including lightweight properties and functional characteristic. The use of lower-density concrete significantly reduces the self-weight of structures, allowing for smaller civil structural design, which in turn reduces construction costs. Additionally, LFC's innate thermal insulation, fire resistance, and sound insulation contributes to more comfort, safety and durable lifestyle.

The integration of natural fibres aligns seamlessly with LFC core purpose of being lightweight, sustainable, and environmentally friendly. These fibers, derived from abundant and sustainable plant sources, offer a more environmentally sustainable alternative to synthetic fibers. While fiber production can exhibit considerable variability due to multiple factors, agricultural innovations have substantially improved natural fibre production efficiency. Likewise, these short, discrete, and thin fibre were incorporated into LFC to increase cracking resistance and improve stress energy absorption, leading to an enhanced mechanical strength and structural integrity. Besides, natural fibre reinforced LFC was renowned for its ease of use and affordability, as the production requires a lower level of technological sophistication and raw materials are predominantly sourced locally, contributing to its economic viability.

As the world's second-largest palm oil producer, Malaysia contributed 25% to the total production of 18.39 million metric tons in 2023, with production projected to increase by 7% annually, reaching 19.7 million metric tons in 2024 (USDA, 2024). The prosperity of the palm oil industry has led to a correspondingly higher volume of waste generation, including Palm oil Frond (POF), Palm-oil Empty Fruit Bunch (PEFB) and Palm Oil Trunk (POT). Among the biomass waste, PEFBs comprise a substantial portion of biomass waste, with approximately 30 to 60 kilograms discarded for every 100 kilograms of fresh fruit bunches processed (Suksaroj *et al.,* 2023). The Palm-oil Empty Fruit Bunches Fibre (PEFBF) is a waste product recovered from the PEFB through a retting process following oil extraction (Momoh & Osofero. 2020) Research indicates that the addition of PEFBF to foam concrete can enhance their mechanical properties without compromising their lightweight nature. Study has revealed that with proper dosage, PEFBF can improved foam concrete compressive strength by up to 14 %, splitting tensile strength increased by 47%, and flexural strength improved by 18% compared to control mix, demonstrating the effectiveness of its fibre-matrix bonding (Rao & Ramakrishna, 2022). Additionally, the addition of PEFBF to LFCs tends to reduce water absorption by filling LFCs void pores with fibres. The thermal conductivity also decreases with more PEFPF was added, due to its inherent low thermal conductivity and cellular porous structure. The dimensional stability, measured by linear shrinkage and expansion of specimen under air curing and tropical weather curing, indicates that LFC with PEFBF exhibits positive effect in dimensional stability and effectively reduces dimensional changes (Lim *et al.,* 2018).

The existing research on PEFBF incorporated composites, while promising, often involve various densities and lacks the long-term strength evaluation associate with microstructural analysis to comprehensively characterise its mechanical behaviour. Therefore, this study presents the feasibility of mixing the PEFBF into LFC, at density of 1300 ± 50 kg/m³, evaluating its mechanical behaviour including compressive, splitting tensile and flexural strengths up to 90-days of curing. The optimum water to cement ratio of LFC-CTR and LFC-PEFBF were obtained by selecting the peak performance from the compressive strength tests on trial mix. A Scanning Electron Microscopy - Energy Dispersive X-rays spectrometry (SEM-EDX) analysis was conducted to identify the fibre-matrix microstructure bonding and chemical composition.

2.0 MATERIALS AND METHODOLOGY

2.1 Materials

This research utilised Orang Kuat branded Ordinary Portland Cement (OPC), fine aggregates, water, SikaAER-50/50 foaming agent, and natural Palm-oil Empty Fruit Bunch Fibre (PEFBF). The OPC, certified under MS ISO 9001, MS ISO 14001, OHSAS 18001, and MS EN 197-1:2014, was sieved to 300 μm and stored in an airtight container. Fine sand, dried in an oven at 100°C for 24 hours to remove moisture, was passed through a 600 μm sieve and had a fineness modulus of 2.27, as determined by sieve analysis (Lim *et al.,* 2013). Tap water with a specific gravity of 1.0 was used for mixing and curing, with the curing tank maintained at a room temperature of 25°C. Foaming agent SikaAER-50/50, compliant with ASTM C796, was combined with water and compressed air to generate foam bubbles with a density of 45 ± 5 kg/m³. PEFBF shown in Figure 1, has specific gravity of 1.3 (Rao & Ramakrishna, 2021), diameter of 0.55 mm, and a length of 20 ± 10 mm was washed, natural dried, and stored as the fibre reinforcement material.

Figure 1: Palm-oil Empty Fruit Bunch Fibre (PEFBF)

2.2 Mix Proportions

In this study, the absolute volume method was applied in designing the mix proportions of both LFC-CTR and LFC-PEFBF. Noted that cement to sand ratio was 1:1 and the PEFBF dosage refer to 1.25% volume fraction. The foam content was adjusted based on the density, while optimised water-to-cement ratio was derived from trial mixes. Table 1 demonstrates the mix proportions of 1m³ LFC for each mix.

Table 1: Mix proportions

Material (kg per 1m³ of composite)	Mix Code	
	LFC-CTR	LFC-PEFBF
Cement	500 [15.87%]	500 [15.87%]
Fine aggregates (sand)	500 [18.86%]	500 [18.86%]
Water	280 [28%]	280 [28%]
PEFBF	-	16.25 [1.25%]
Foam /Air bubbles content	[37 ± 2%]	[36 ± 2%]
Density	1300 ± 50 kg/m³ [100%]	
W/C ratio	0.56 to 0.66 by interval of 0.02	
Foaming ratio	1 (foaming agent) : 20 (water)	

Note: The [%] expressed in terms of volumetric percentage per 1m³ of composite

2.3 Specimens Preparation and Testing Methods

To establish the optimal water-to-cement (W/C) ratio for achieving maximum compressive strength, a series of trial mixes were subjected to compressive strength testing at 7, 14, and 28 days. Using the determined optimal W/C ratio, LFC-CTR and LFC-PEFBF specimens were fabricated for subsequent compressive, splitting tensile, and flexural strength evaluations. To investigate the interfacial bonding and chemical composition of the LFC-PEFBF composite, Scanning Electron Microscopy with Energy-Dispersive X-Ray Spectrometry (SEM-EDX) analysis was performed on the LFC-PEFBF samples. Prior to casting, essential fresh property tests, including flow table, inverted slump, and fresh density test were conducted.

2.4 Density Test

Following the standardisation ASTM C138 (2021), the fresh LFC-CTR and LFC-PEFBF samples, were prepared in a 1-litre container. The container was initially tared to zero on a weighing machine. After overfilling with the fresh LFC mixture, the material was compacted through gentle tapping on the container's sides to ensure uniform consolidation. Excess LFC was struck off, and any residual material on the exterior was wiped clean. The container and its contents were then weighed to determine the fresh density of the LFC samples.

The process is repeat with foam addition until reaching target density of 1300 ± 50 kg/m³ in accordance with manufacturer's specification (Jones & McCarthy, 2005).

2.5 Flow Table Test

The flowability of the LFC, prior to the incorporation of foam, was evaluated through the flow table spread test, conducted in accordance with ASTM C 230 (2021). This standard protocol entails positioning the LFC mortar within a conical mold on the flow table, subsequently removing the mold and subjecting the mortar to 25 drops at a controlled speed of approximately 100 revolutions per minute. The resulting spread of the mortar was then quantified by measuring its average diameter from four distinct angles.

2.6 Inverted Slump Test

The inverted slump test, as outlined in ASTM C 1611 (2021), measures the workability of fresh LFCs. The test involves placing a dampened slump cone on a level surface, filling it with LFC mortar without tamping or vibrating, and then lifting the cone vertically to a height of 23 ± 8 cm within 3 seconds. The largest and smallest diameters of the spread are measured to the nearest 5mm. For this project, measurements were taken from four angles, and the difference between the largest and smallest diameters was considered in the analysis.

2.7 Compression Test

Compressive strength testing was conducted on 100mm cubic specimens of LFCs according to BS EN 12390-3 (2019). An Instron 5582 testing machine was used to apply a compressive load at a specified rate until failure. Prior to testing, the specimens were oven-dried for 24 hours after removal from water storage, then subjected to evaluation up to 90 days of curing. Dimensional measurements were taken to determine the cross-sectional area. The specimens were then centred in the testing machine and loaded at a constant rate of 0.02 mm/s until failure. The mean compressive strength of three specimens was calculated for each lightweight foamed concrete mix.

2.8 Splitting Tensile Test

Splitting tensile strength testing was performed on 100mm diameter x 200mm height cylindrical specimens of LFC according to BS EN 12390-6 (2019). Similarly, an Instron 5582 testing machine was used to apply an axial load at a specified rate until failure. Prior to testing, the specimens were oven-dried for 24 hours, removed from water storage, with testing conducted throughout 90-days curing period. The specimens were placed in a steel mould with thin plywood bearing strips at the top and bottom to distribute the load evenly. A constant loading rate of 1.2 mm/min was applied until failure. The mean splitting tensile strength of three specimens was calculated for each lightweight foamed concrete mix.

2.9 Flexural Test

Flexural strength testing was conducted on 25mm x 25mm x 250mm prismatic specimens of LFCs according to BS EN 12390-5 (2019). Identically, an Instron 5582 testing machine was used to apply a centre-point load at a specified rate until failure. To standardise testing conditions, specimens were oven-dried for 24 hours prior to evaluation, ensuring complete drying before evaluation up to 90 days of curing. Support blocks were positioned at 10mm offsets from both ends of the specimens. A constant loading rate of 0.1 mm/min was applied until failure. The mean flexural strength of three specimens was calculated for LFC mix.

3.0 MATERIALS AND METHODOLOGY

3.1 Compression Test (Trial Mix)

Figure 2 shows the compressive strength development of LFC-CTR and LFC-PEFBF at 7, 14, and 28 days for different water-cement (W/C) ratios.

Both mixes exhibited a general trend of increasing compressive strength with decreasing W/C ratio and increasing age. However, LFC-CTR demonstrated slightly higher compressive strength values than LFC-PEFBF at early ages, while LFC-PEFBF exhibited higher compressive strength at 28 days. The optimal W/C ratios for both mixes were found to be 0.58 and 0.62, respectively, where their highest compressive strength values were achieved. These results suggest that the incorporation of PEFBF requires more water to achieve optimal strength development, potentially preventing fibre balling and agglomeration (Wang *et al.,* 2024).

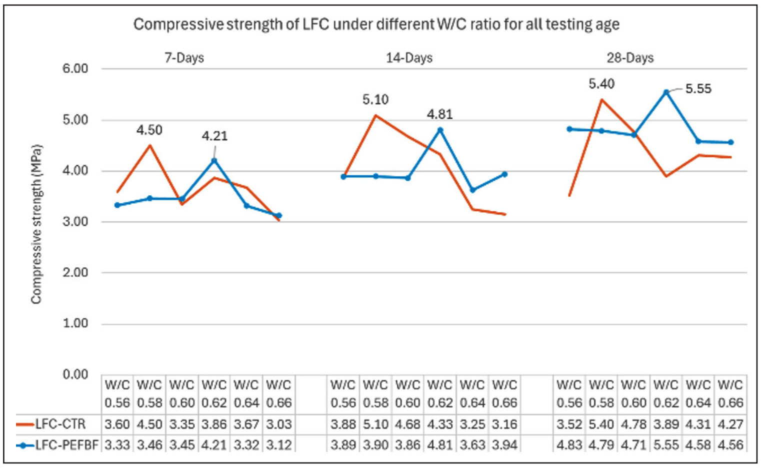


Figure 2: Trial mix results

3.2 Fresh Properties

To assess the workability and fresh properties of the LFC-CTR and LFC-PEFBF, a series of tests including fresh density, flow table, inverted slump test was conducted. Table 2 summarises the results, including the optimal water-to-cement (W/C) ratio, fresh density, flow table spread, average inverted slump diameter, consistency, and stability.

Both LFC-CTR and LFC-PEFBF exhibited comparable workability characteristics, with both mixes demonstrating high flow table spread and average inverted slump diameter. However, LFC-PEFBF had a slightly lower fresh density and workability indicators compared to LFC-CTR, due to the presence of PEFBF fibres. The consistency and stability values were within acceptable limits for both mixes. LFC-CTR exhibited

Table 2: Summary of fresh properties

Sample	Optimum W/C Ratio	Fresh Density (kg/m^3)	Flow Table Spread, (number of drop)	Average Inverted Slump Diameter (mm)	Consistency[a]	Stability[b]
LFC-CTR	0.58	1348	>250 (9 drops)	650	1.045	1.074
LFC-PEFBF	0.62	1260	>250 (13 drops)	605	0.954	0.934

[a]Note 1: Consistency refer to fresh to target density ratio, closer to unity indicate well balanced mix design.
[b]Note 2: Stability refer to fresh to hardened density ratio, closer to unity indicates minimal changes in air, water, and other components during hydration process.

a consistency and stability greater than unity, indicating that the hardened mix was lighter than its fresh state. This is due to bubble coalescence during the hardening process, resulting in larger pores and a reduction in hardened density. Conversely, LFC-PEFBF had a consistency and stability slightly lower than unity, suggesting bubble bursting and buoyant foam collapse, due to lower paste viscosity and longer paste setting time (Xiao *et al.,* 2023).

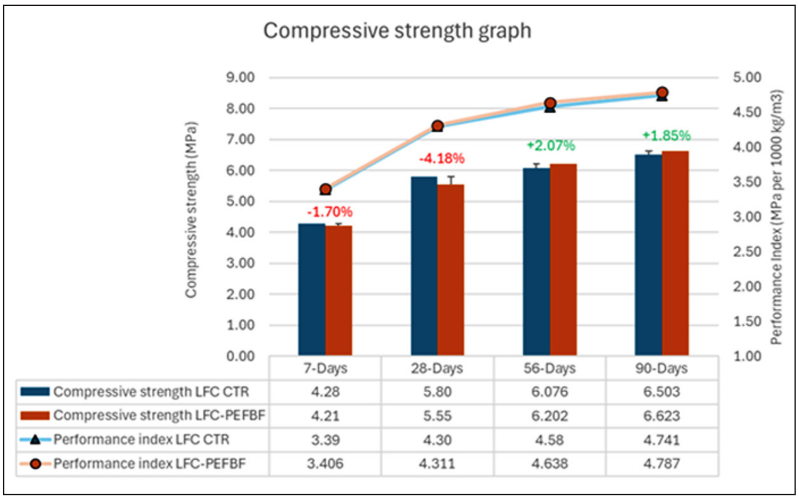


Figure 3: Compressive strength graph

3.3 Compression Test

Figure 3 shows the comparison of compressive strength for LFC-CTR and LFC-PEFBF at different curing age. The performance index, calculated as compressive strength per 1000 kg/m^3 density, provides a more nuanced comparison on different LFC at same density.

Both LFC types exhibited an increase in compressive strength over time, provided with higher strength of LFC-CTR (5.8MPa) than LFC-PEFBF (5.55MPa) at standard 28-days curing age. However, LFC-PEFBF demonstrated a slower initial strength gain but surpassed LFC-CTR at 2% increment rate in late-stage development, especially at 56 days. This suggests that PEFBF inclusion in LFC requires a longer curing period for optimal hydration and fibre-matrix bonding. The increased hydration products at later ages facilitate improved stress transfer, leading to superior compressive strength in LFC containing fibre. Notably, LFC-PEFBF's slightly higher performance index indicates that palm oil empty fruit bunch fibre enhances the structural efficiency of LFC. A similar finding, with the overall performance index of natural fibre inclusion outperforming the control mix but with no significant compressive strength enhancement, was found in previous research (Lim *et al.,* 2018).

3.4 Splitting Tensile Test

Figure 4 demonstrates the comparative analysis of splitting tensile strength for LFC-CTR and LFC-PEFBF. The summary of splitting tensile strength result associated with performance index is illustrated in Figure 4.

The splitting tensile strength analysis of LFC-PEFBF reveals distinct trends from compressive strength analysis. Notably, LFC-PEFBF consistently demonstrated a marginally higher splitting tensile strength gain than LFC-CTR throughout the curing period. Figure 4 demonstrates its significant early strength gain of 23%, followed by a slight decline to 19% in later stages. Subsequently, a 13% strength gain suggesting the possible of LFC-PEFBF ongoing strength development after 90-days of curing. Nonetheless, a more pronounced gap disparity between the performance index lines of the two LFCs, highlighting the significant tensile strength enhancement provided by LFC-PEFBF. Similar findings reported by Abbas *et al.* (2022) attribute the substantial improvement in tensile strength to the strong interlock and adhesive bond between the natural fibres and the cement matrix. This enhanced internal confinement effectively counteracts lateral expansion under transverse loading conditions, leading to splitting tensile strength improvement.

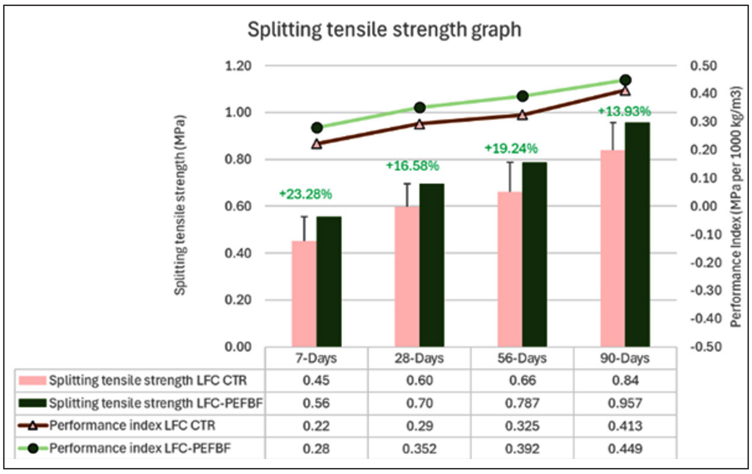
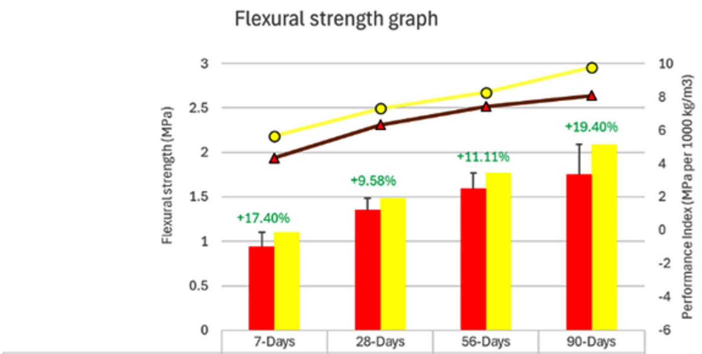


Figure 4: Splitting tensile strength graph

3.5 Flexural Test

This study investigates the flexural strength development of LFC CTR and LFC-PEFBF over a 90-day curing period. The results presented in Figure 5 demonstrate a clear comparison between the two materials.



	7-Days	28-Days	56-Days	90-Days
Flexural strength LFC CTR	0.937	1.357	1.593	1.753
Flexural strength LFC-PEFBF	1.10	1.49	1.77	2.093
Performance index LFC CTR	4.331	6.32	7.434	8.08
Performance index LFC-PEFBF	5.64	7.30	8.258	9.782

Figure 5: Flexural strength graph

Similar to splitting tensile analysis, LFC-PEFBF exhibited a 17.40% increase in flexural strength compared to LFC-CTR at 7 days. This trend continued throughout the curing period, with LFC-PEFBF demonstrating a 19.40% higher flexural strength than LFC-CTR at 90 days, indicating continuous strength development at later ages. The significantly increment in performance index further supports the development of an effective fibre bridging mechanism within LFC. By bridging across microcracks the natural fibres act as cracks inhibitors, facilitating fracture energy absorption and increasing fracture energy capacity, improving structural integrity and flexural strength (Abbas *et al.* 2022).

3.6 SEM-EDX Test

A Scanning Electron Microscope - Energy Dispersive X-rays spectrometry (SEM-EDX) test was conducted to provide highly precise magnified images of concrete details by scanning the specimen surface and presenting the chemical composition exist. Figure 6 illustrates the SEM result of LFC-PEFBF under various magnifications, and Figure 7 presents the result of EDX test of LFC-PEFBF.

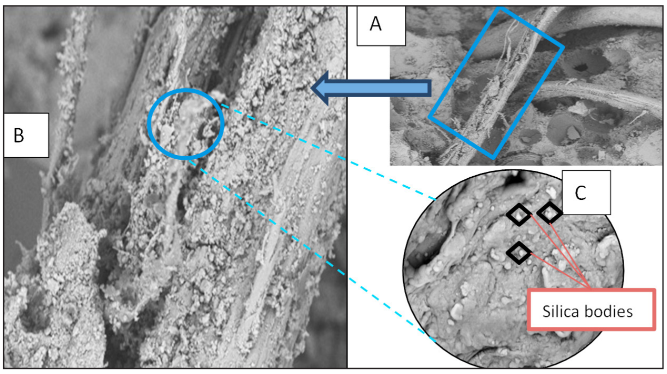
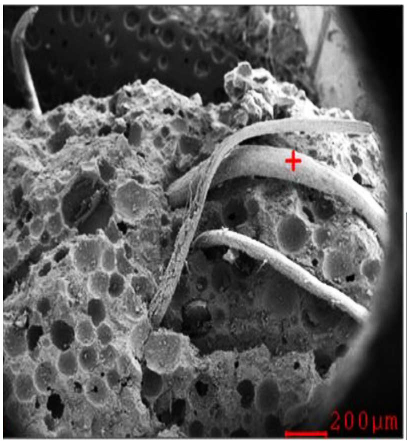


Figure 6: Microstructural images of LFC-PEFBF at curing age of 56 days: (A) 60x, (B) 500x, (C) 1000x, of magnification

The SEM micrograph reveals the synergistic interaction between PEFBF and the LFC matrix. Figure 6A shows the LFC's cellular structure infiltrated with PEFBF, forming an interconnected fibre network. Figure 6B highlights the complete coverage of the PEFBF surface with hydration products, indicative of robust fibre-matrix bonding for efficient stress transfer. Figure 6C demonstrates the PEFBF high surface roughness, presenting the mechanical interlocking mechanism between fibre and matrix, contributing to enhanced strength. Additionally, Figure 6C reveals the presence of silica bodies naturally occurring on the PEFBF surface. While silica bodies have been shown to enhance fibre-matrix interface strength by limiting sliding motion (Omar *et al.,* 2014), some studies suggest that alkaline treatment to remove these bodies can create a rougher surface and expose more amorphous regions of the fibre, potentially leading to improved bonding characteristics (Ibrahim *et al.,* 2015).

EDX analysis in Figure 7 reveals the elemental composition of the LFC with and PEFBF. The LFC primary compound are made of calcium (Ca), silicon (Si), and oxygen (O), representing key components of mortar and concrete. The PEFBF contains organic chemical compound such as carbon (C) and oxygen (O). From Figure 7, after 56-days of curing, surface of LFC-PEFBF demonstrate a higher concentration of calcium (Ca) and silicon (Si) from the cement paste, suggesting a successful covering and adhesion of the binder onto the fibre surface. These findings confirm the effective integration of PEFBF into the cement-based matrix, leading to enhanced mechanical properties.



Element	Wt%	At%
CK	01.97	15.77
OK	03.57	21.43
ZnL	01.01	01.48
MgK	00.52	02.04
AlK	00.97	03.45
SiK	01.07	03.67
AuM	73.86	36.04
PbM	07.69	03.57
PdL	06.59	05.95
CaK	02.76	06.61
Matrix	Correction	MThin

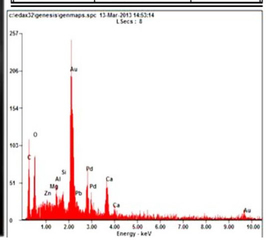


Figure 7: EDX report of LFC-PEFBF

4.0 CONCLUSION

Based on the result data obtained the aim and objectives of this research are accomplished. Within the scope of work of research, the following conclusions are drawn:

1. The optimised W/C ratios for LFC mixes identified to maximise strength along 90-days of curing presenting LFC-CTR at 0.58 and LFC-PEFBF at 0.62. All specimens achieved target density of 1300±65 kg/m³ within tolerance.
2. For fresh properties and workability, LFC-CTR outperformed LFC-PEFBF, suggesting the inclusion of fibre slightly reducing the workability.

3. Compression test results indicate that LFC-PEFBF requires a longer curing period to achieve optimal hydration and develop stronger bonds with PEFBF, exhibiting superior compressive strength after 56 days compared to that of LFC-CTR.
4. The incorporation of PEFBF into LFC significantly improving its splitting tensile and flexural strengths, achieving a notable standard 28-days strength improvement up to 16% and 9%, respectively. These enhancements underscore the potential of LFC-PEFBF to serve as a durable and reliable material for structural applications, contributing to the construction of more resilient buildings.
5. SEM-EDX analysis confirms the enhanced surface roughness of PEFBF, fostering superior mechanical interlock within the LFC matrix. The abundance of calcium and silicon on the PEFBF surface indicates effective coverage and improved bonding with the matrix after 56 days of hydration.

5.0 ACKNOWLEDGEMENT

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- **Siong Kang Lim:** Conceptualisation, study design, and supervision.
- **Hao Yee Richmond Chong:** Data collection, methodology, and formal analysis.
- **Ming Kun Yew:** Writing—original draft preparation and literature review . ■

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