DIMENSIONAL STABILITY OF LIGHTWEIGHT FOAMED CONCRETE INCORPORATED WITH DIFFERENT VOLUME FRACTIONS OF TREATED KENAF FIBRE

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Abstract

Lightweight foamed concrete (LFC) is recognised as a more sustainable option than traditional concrete; however, its high porosity typically results in low mechanical strength and poor dimensional stability. This study explores the use of Treated Kenaf Fibres (TKF) as reinforcement in LFC to enhance its overall performance. Kenaf fibres were chemically treated with sodium hydroxide (NaOH) to improve their adhesion with the cementitious matrix, and incorporated at different volume fractions (0.25%, 0.5%, 0.75%, and 1.0%). The mechanical performance, namely compressive, flexural, and splitting tensile strength, was assessed, along with shrinkage-related dimensional changes under both indoor and outdoor curing environments. Findings revealed that TKF reinforcement notably enhanced mechanical strength by mitigating microcracks and improving stress distribution. TKF-incorporated mixes exhibited improved dimensional stability and reduced shrinkage compared to the control mix, particularly under indoor curing conditions. Nevertheless, high fibre dosage reduced workability and caused greater performance inconsistency. The optimal balance was achieved at 0.75% volume fraction, delivering significant strength enhancement and improved shrinkage resistance. Overall, the study demonstrates that TKF serves as an effective and environmentally friendly reinforcement for LFC, improving both mechanical properties and dimensional stability.

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Lightweight Foamed Concrete, Kenaf fibre, Dimensional stability, Mechanical properties

1.0 INTRODUCTION

This study focuses on examining the effects of incorporating TKF into LFC, with particular attention to dimensional stability at different fibre volume fractions. Kenaf fibre, recognised for its natural and environmentally friendly characteristics, is evaluated for its potential to enhance the mechanical performance of LFC. Nevertheless, the introduction of kenaf fibre into the cementitious matrix may influence the material's dimensional stability. The study remains aligned with the aim of identifying sustainable reinforcement materials that can improve both the stability and overall mechanical performance of LFC.

In recent years, sustainability has become a major priority across various industrial sectors, particularly within the construction industry due to its substantial environmental impact. Traditional construction practices heavily depend on materials and processes that generate high levels of carbon emissions. The carbon-intensive nature of conventional building materials, coupled with energy-demanding manufacturing processes, has contributed significantly to environmental degradation. Consequently, there is a growing emphasis on adopting more sustainable construction approaches and eco-friendly materials to reduce the industry's carbon footprint and support global environmental conservation efforts.

The use of Kenaf fibre in LFC offers potential benefits for improving its properties and supporting sustainable construction. However, the intrinsic hydrophilic nature of Kenaf fibre may lead to long-term issues in structural strength and load-bearing performance (Lim, 2025). By treating the fibre using alkaline solution, the removal of fibre surface impurities tends to result in overall interfacial bonding enhancement. While research has yet to determine the optimal fibre volume fraction to be incorporated, past studies have shown that TKF can enhance tensile and flexural strength when incorporated into cement matrix (Lam, 2015) (Hashim, 2024).

This research aims to produce and evaluate LFC incorporating TKF under various fibre volume fractions (0.25%, 0.5%, 0.75%, 1.0%). The study focuses on developing both LFC without kenaf fibre (LFC-Control) and LFC with treated kenaf fibre (LFC-TKF), targeting a density of 1200 $\pm$ 50 kg/m^3. By determining the optimal Kenaf fibre volume fraction, the effectiveness of natural fibre reinforcement can be proven through improved dimensional stability and mechanical properties. In addition, the mechanical properties evaluation involves compressive, flexural, and splitting tensile strengths, subjected to different fibre volume fractions.

2.0 MATERIALS AND METHODOLOGY

2.1 Materials

Ordinary Portland Cement (OPC), fine aggregates, water, foam, and TKF were used in the production of LFC in this study, with all materials prepared under controlled procedures to ensure consistency and minimise moisture-related variability. OPC (Orang Kuat, YTL Sdn. Bhd.), compliant with ASTM C150 and

MS EN 197-1, was sieved through a 300 μm sieve and stored in airtight conditions prior to mixing to ensure uniform particle size and stable hydration behaviour. Fine aggregates conforming to ASTM C33 were sieved to 600 μm, oven-dried at 70 °C for 24 h to remove residual moisture and sealed until use (ASTM C33, 2018). Clean tap water satisfying ASTM C1602 was employed for both mixing and curing, with curing conducted at ambient laboratory temperature (26 °C) to promote stable hydration and strength development (ASTM C1602, 2006). A synthetic foaming agent (SIKA AER-50/50), compliant with ASTM C796, was prepared at a 1:20 foaming agent-to-water ratio and generated using the pre-foam method under compressed air at 0.5 MPa. Kenaf fibres extracted from the bast were manually cut to lengths of 3 ± 1 cm and subjected to alkali treatment using a 1.5 M NaOH solution for 12 hours at a fibre-to-solution ratio of 1:20, followed by outdoor air-drying to prevent thermal degradation. Both treated and untreated fibres (Figure 1) were manually separated prior to mixing to ensure uniform dispersion within the LFC matrix.

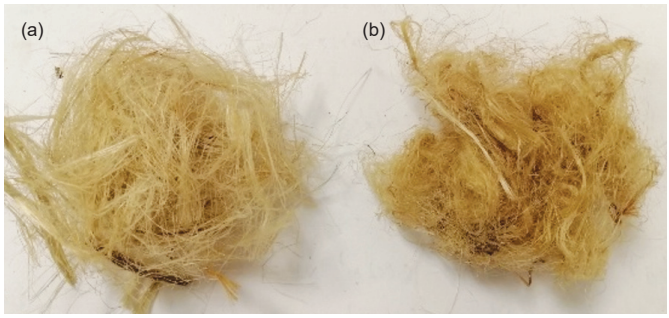


Figure 1: Kenaf fibre: (a) Untreated; (b) Treated

2.2 Mix Proportions

In this study, the mix proportions for LFC-Control, LFC-TKF-0.25, LFC-TKF-0.5, LFC-TKF-0.75 and LFC-TKF-1.0 were designed using the absolute volume method. The water-to-cement ratio was set at 0.60. Table 1 presents the mix proportions of LFCs for each mixture.

2.3 Specimens' Preparation

Specimen preparation was carried out in two stages to establish an optimal mix design and to support subsequent performance evaluation. Initially, trial mixes were produced and cast into cubes (100 mm), cylinders (100 mm diameter × 200 mm height), and prisms (160 × 40 × 40 mm) for compressive strength, splitting tensile strength, and flexural strength tests, respectively, at curing ages of 7 and 28 days. Fresh-state properties, including density, flow table spread, and inverted slump, were also measured during this stage to assess workability and stability. Based on the combined mechanical and fresh property results, the optimal volume fraction was determined and adopted for all subsequent specimen casting. Using this optimised mix, additional prism specimens (300 × 75 × 75 mm) were prepared for plastic shrinkage and drying shrinkage tests, ensuring consistency and comparability across all experimental evaluations.

2.4 Fresh Properties Test

The fresh density test for LFC-TKF was carried out in accordance with ASTM C796. A 1-liter container was used, filled with the LFC mixture, and the excess material was scrapped off before weighing (ASTM C796, 2004). The mixture was then returned to the mixing container, additional foam was added, and the mass was measured again. This procedure was repeated until the target density of 1200 ± 50 kg/m^3 was achieved. The slump cone was positioned upside down at the centre of a metal tray, and the concrete mixture was poured into it, with any excess material scrapped off at the top. The cone was then carefully lifted, allowing the mixture to spread, and the diameter of the resulting flow was measured. This test was carried out in accordance with standard slump flow test (ASTM C1611, 2009). Before incorporating stable foam into the mortar mix, a flow table test was performed. This test involves manually rotating and dropping the table while recording the number of drops required for the cement paste to spread to the edge of the metal plate. The procedure was conducted in accordance with standard flow table test (ASTM C230, 2009).

2.5 Compression Test

Compressive strength testing was carried out on concrete cubes in accordance with BS EN 12390-3. Prior to testing, flat surfaces of the cubes were selected as the top and bottom faces to ensure uniform load distribution. A constant loading rate of 0.1 kN/s was applied until failure occurred. The maximum load sustained by the specimen before failure was recorded and used to calculate the corresponding compressive strength.

Table 1: Mix proportions

Material (kg per 1m^3 of Composite)	Mix Code				
	LFC-Control	LFC-TKF-0.25	LFC-TKF-0.5	LFC-TKF-0.75	LFC-TKF-1.0
Cement	462	460.39	459.25	458.11	456.96
Fine aggregates (sand)	462	460.39	459.25	458.11	456.96
Water	258.72	276.24	275.55	274.86	274.18
Kenaf fibre	-	2.98	5.95	8.90	11.90
Foam content	1 (foaming agent) : 20 (water)				
Density	1200 ± 50 kg/m^3				
W/C ratio	0.6				
KF volume fractions	-	0.25 %	0.5%	0.75%	1.0%

2.6 Splitting Tensile Test

The splitting tensile strength test was conducted in accordance with ASTM C496. Cylindrical concrete specimens were prepared accordingly to ensure proper curing and testing at the specified testing ages (ASTM C496 2004). Two perpendicular lines were drawn along the specimen's length to aid in accurate alignment of the loading strips. Each specimen was then positioned horizontally between the loading strips in the testing machine, ensuring correct alignment with the marked lines. A continuous load was applied at a constant rate of 0.2 kN/s until failure occurred. The maximum load at failure was recorded, along with the observation of the resulting crack pattern, whether straight or inclined.

2.7 Flexural Test

The flexural strength test was conducted in accordance with ASTM C1609, which specifies the use of rectangular concrete beam specimens. The beams were prepared following the standard requirements, which permit alternative dimensions despite the recommended sizes. During testing, each specimen was placed perpendicularly on the machine supports, ensuring that the span length and support conditions met the standard specifications (ASTM C1609, 2019). A uniform load was then applied at the centre of the beam using a three-point bending method setup, providing equal support on both sides. Throughout the test, the specimen's deflection and applied load were continuously monitored and recorded. The loading process continued until failure occurred, and the maximum load at the point of failure was documented.

2.8 Plastic Shrinkage Test

Plastic shrinkage was evaluated by monitoring early-age linear dimensional changes occurring during the initial hardening stage of the specimens. Immediately after casting, prism specimens were exposed to ambient laboratory conditions, with average temperature of 26 ± 2 °C and relative humidity of 55 ± 5%. Linear length changes were measured at predetermined time intervals within the first 24 hours using a digital vernier caliper (Figure 2). Plastic shrinkage was reported as the change in specimen length, expressed in micrometres (μm).

2.9 Drying Shrinkage Test

Drying shrinkage testing was conducted in accordance with ASTM C157 to evaluate time-dependent dimensional changes resulting from moisture loss. After demoulding 24 hours, specimens were cured under two different environments: indoor laboratory conditions (average temperature of 26 ± 2 °C and relative humidity of 55 ± 5%) and outdoor exposure conditions subjected to natural temperature and humidity fluctuations (ASTM C157, 2024). Specimen lengths were measured using a length comparator (Figure 3) at regular intervals up to 30 days. Drying shrinkage was reported as linear length change, expressed in micrometres (μm).



Figure 2: Plastic shrinkage test setup

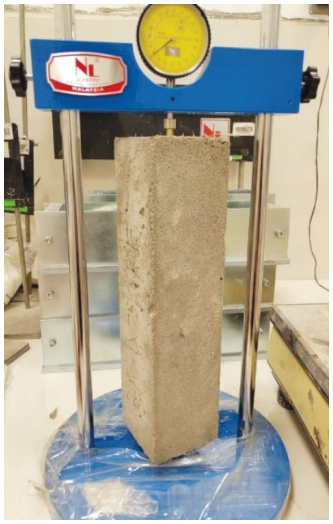


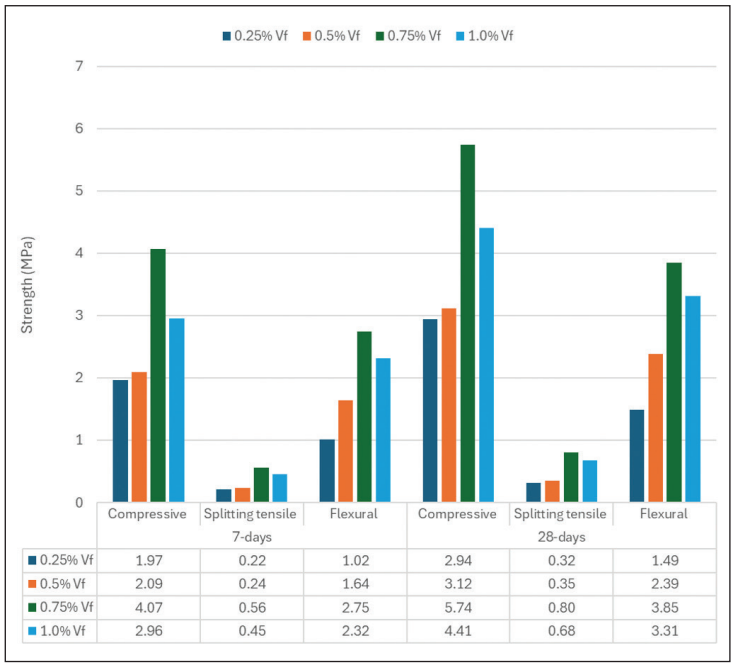
Figure 3: Drying shrinkage test setup

3.0 RESULTS AND DISCUSSION

3.1 Trial Mix

In this study, trial mixes with different fibre volume fractions (LFC-TKF-0.25, LFC-TKF-0.5, LFC-TKF-0.75 and LFC-TKF-1.0) were cured for 7 and 28 days to identify the optimal dosage. The outcomes of these trial mixes are presented in Figures 4 below.

Based on the 28-day mechanical strength results, the optimal volume fraction for each mix was determined. The specimens reached an optimal volume fraction at 0.75, achieving a compressive strength of 5.74 MPa, tensile strength of 0.8 MPa and flexural strength of 3.85 MPa. The LFC-TKF-1.0 achieved compressive strength of 4.41 MPa, tensile strength of 0.68 MPa and flexural strength of 3.31 MPa. The optimal volume fractions 0.75%Vf were used for the subsequent actual casting.



	7-days			28-days		
	Compressive	Splitting tensile	Flexural	Compressive	Splitting tensile	Flexural
0.25% Vf	1.97	0.22	1.02	2.94	0.32	1.49
0.5% Vf	2.09	0.24	1.64	3.12	0.35	2.39
0.75% Vf	4.07	0.56	2.75	5.74	0.80	3.85
1.0% Vf	2.96	0.45	2.32	4.41	0.68	3.31

Figure 4: Trial mixes results at different treated kenaf fibre volume fraction (Vf) at 7 & 28 days

Table 2: Summary of fresh properties

Sample	Average fresh density (kg/m³)	Average hardened density (kg/m³)	Inverted slump spread diameter (mm)	Flow table (No. drop)	Consistency[a]	Stability[b]
LFC-TKF-0.25	1185.5	1182.7	587.4	18	0.9879	1.0024
LFC-TKF-0.5	1238.2	1230.4	546.2	23	1.0318	1.0063
LFC-TKF-0.75	1218.1	1223.2	484.6	23	1.0151	0.9958
LFC-TKF-1.0	1223.7	1218.3	431.3	25	1.0193	1.0044

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

3.2 Fresh Properties

The fresh properties of the concrete were assessed during casting. Workability at different kenaf fibre volume fractions was evaluated using two tests: the flow table test and the inverted slump test. The results obtained from these tests are presented in Table 2.

For all tested fibre volume fractions, the fresh and hardened densities stayed within a narrow range of 1182–1238 kg/m³, showing only minor variation of approximately ±2%. The inverted slump spread diameter decreased progressively from 587.4 mm to 431.3 mm as the TKF volume fraction increased from 0.25% to 1.0%, reflecting a reduction in workability attributable to fibre interlocking and increased matrix resistance to flow. Consistency values (0.9879–1.0193) and stability values (0.9958–1.0063) were consistently near unity, indicating that LFC closely matched the target density and experienced minimal density loss after hardening. Overall, these results demonstrate that the mixes maintained good consistency and stability across all fibre volume fractions.

3.3 Plastic Shrinkage

Plastic shrinkage refers to the slight reduction in concrete volume during the hardening stage due to water loss. The plastic shrinkage of the specimens was measured using a digital dial gauge. Figure 5 presents the plastic shrinkage results for the three specimens: LFC-Control, LFC-TKF-0.75, and LFC-TKF-1.0. The reduced plastic shrinkage observed in fibre-reinforced specimens is consistent with previous studies reporting that natural fibres can restrain early-age microcrack formation by providing internal tensile resistance during the plastic stage. The present results further demonstrate that alkali-treated kenaf fibre is effective in mitigating early-age shrinkage in LFC, even at sub-optimal fibre volume fractions.

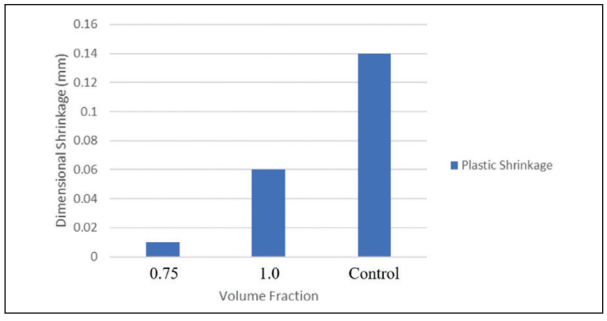


Figure 5: Plastic shrinkage of LFC specimens

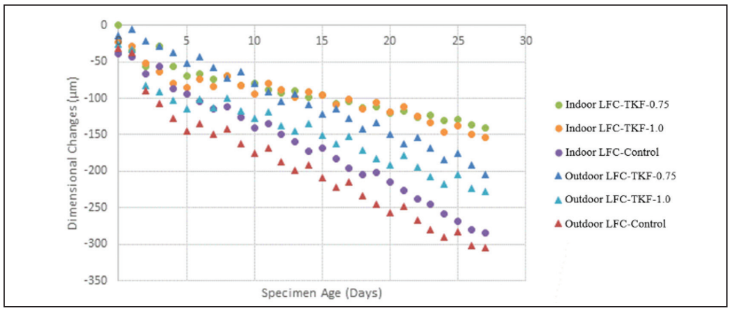


Figure 6: Dimensional changes of LFC over 30 days

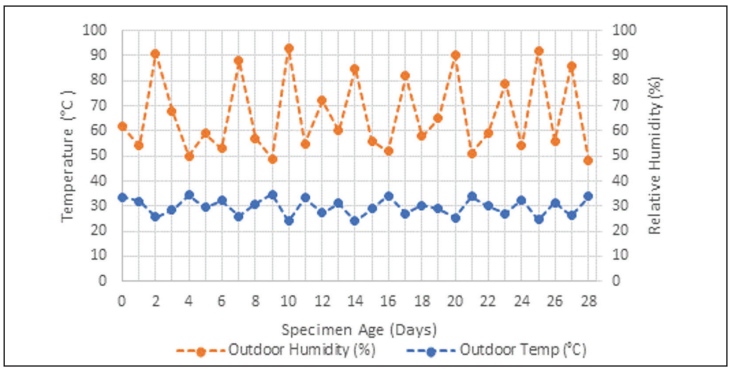


Figure 7: Outdoor temperature and relative humidity record

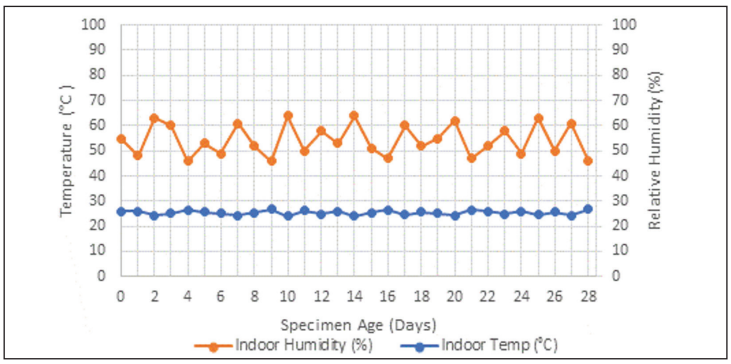


Figure 8: Indoor temperature and relative humidity record

3.4 Drying Shrinkage

This study investigated the dimensional stability of LFC, with and without TKF, over a monitoring period of 30 days under both indoor and outdoor curing environments. Similar drying shrinkage behaviour has been widely reported in lightweight and fibre-reinforced cementitious composites, where moisture loss is amplified by high porosity and low matrix density. However, the present study extends existing findings by examining shrinkage development under both controlled indoor conditions and natural outdoor exposure, providing a more realistic assessment of dimensional stability in service environments.

For the indoor specimens, shrinkage was less obvious, due to the relatively consistent temperature and humidity (Figure 8). The control mix without fibres (Indoor LFC-Control) experienced the greatest shrinkage, reaching nearly −200 μm by Day 30 (Figure 6). Incorporating TKF reduced shrinkage, with the fibre content (Indoor LFC-TKF-0.75) demonstrating the most stable performance at approximately −120 μm. This trend aligns with previous studies indicating that fibre reinforcement enhances dimensional stability by bridging microcracks and limiting moisture-induced deformation. The superior performance of LFC-TKF-0.75 suggests that an optimal fibre dosage maximises shrinkage restraint without disrupting matrix continuity, which is consistent with reported observations in natural fibre-reinforced concrete systems.

Outdoor specimens showed significantly greater shrinkage due to more severe conditions (Figure 7), including temperature fluctuations, direct sunlight, and variable humidity. The outdoor LFC-Control mix shrank the most, exceeding −300 μm by Day 30 (Figure 6). Fibre-reinforced mixes (Outdoor LFC-TKF-0.75 and 1.0) also experienced shrinkage, but it was lower than the control.

Comparable observations have been reported in fibre-reinforced composites exposed to aggressive environmental conditions, where fluctuating temperature and humidity accelerate moisture loss and dimensional instability. The present findings demonstrate that while TKF mitigate shrinkage under outdoor exposure, their effectiveness is partially reduced compared to indoor conditions, underscoring the dominant role of environmental factors in governing long-term dimensional behaviour.

3.5 Scanning Electron Microscopy (SEM) Analysis

A Scanning Electron Microscope (SEM) analysis was conducted using the HITACHI S-3400N, following ASTM C1723 to capture high-resolution images of kenaf fibres and concrete surfaces, allowing detailed observation of their surface morphology and fibre–matrix bonding, particularly at the Interfacial Transition Zone (ITZ). The SEM test was performed on fractured fibre reinforced concrete surfaces after compression testing. Since SEM requires conductive samples to avoid electrostatic distortion, the concrete and kenaf fibres were coated with a thin gold layer before being placed in the vacuum chamber and scanned at magnifications of 1000×.

The microstructural morphology of the LFCs, as captured at 1000× magnification, reveals the critical impact of fiber reinforcement on matrix integrity (Figure 9). The control specimen (LFC-Control) displays a characteristic porous matrix with inherent microcracking (Figure 9a), representing the baseline fragility of unreinforced foamed concrete. Upon the incorporation of 0.75% NaOH-treated kenaf fibers (Figure 9b), the ITZ shows evidence of enhanced interfacial bonding; the alkaline treatment process effectively removed fibre surface impurities, increasing surface roughness and exposing cellulose to facilitate better adhesion with hydration products (Chong, 2025). However, at the higher volume fraction of 1.0% (Fig. 9c), the matrix exhibits a denser crystalline structure, specifically ettringite needles and calcium hydroxide (portlandite) plates. While these minerals signify healthy cement hydration, the LFC-TKF-1.0 specimen shows more pronounced microcracking compared to the 0.75% mix. This phenomenon is likely attributed to the hydrophilic nature of the high fibre volume, which can be explained through over absorption of moisture from the surrounding paste during the curing process (Lim, 2025).

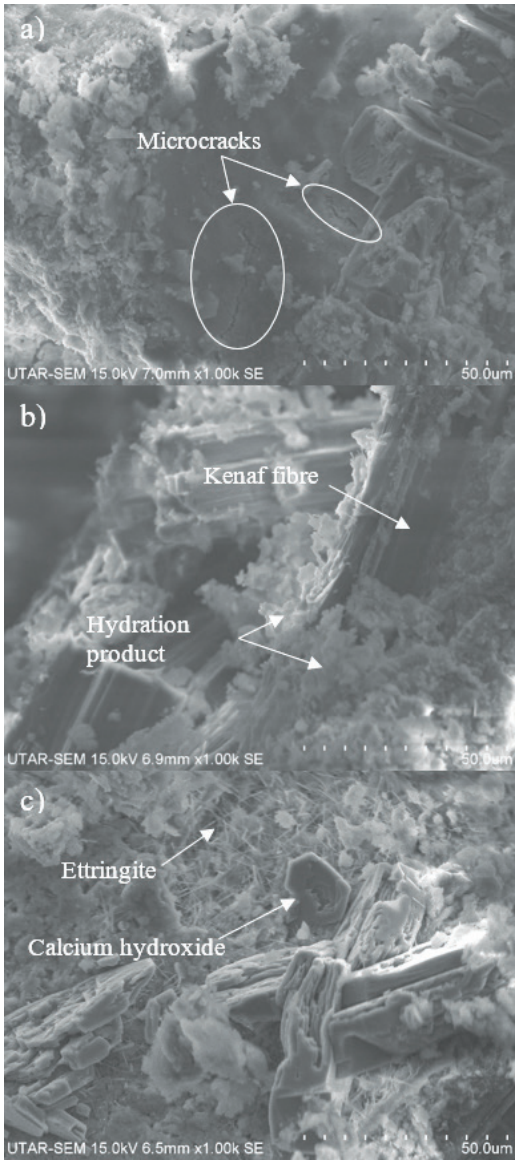


Figure 9: SEM images 1000×: (a) LFC-Control; (b) LFC-TKF-0.75 (c) LFC-TKF-1.0

The microstructural features observed through SEM provide mechanistic support for shrinkage and strength results. Improved fibre–matrix interfacial bonding and reduced void formation in LFC-TKF-0.75 correspond with its enhanced dimensional stability and mechanical performance. In contrast, the increased microcracking at higher fibre content (1.0%) explains the greater shrinkage variability and performance inconsistency, which has also been reported in fibre-reinforced cementitious composites with excessive fibre dosage.

4.0 CONCLUSION

This study demonstrates that the incorporation of TKF markedly affects the fresh, mechanical, and shrinkage behaviour of LFC, with optimal performance at a 0.75% fibre volume fraction. While LFC-TKF-0.25 exhibited the highest workability, mechanical strengths peaked in LFC-TKF-0.75, achieving compressive, splitting tensile, and flexural strengths of 5.74, 0.8, and 3.85 MPa,

respectively. This enhancement is attributed to improved fibre–matrix bonding, whereas excessive fibre content (1.0%) slightly reduced performance due to internal disruption. LFC-TKF-0.75 also showed the most stable dimensional behaviour, with minimal plastic (0.1 mm) and drying shrinkage, indicating effective moisture regulation. SEM analysis confirmed increased surface roughness and cellulose exposure of treated fibres, promoting mechanical interlocking and reducing interfacial voids. Limitations include laboratory-scale testing, potential variability in fibre dispersion, and restricted climatic conditions. Future work should explore long-term performance across diverse environments, optimised fibre treatments, and large-scale applications to further validate TKF in LFC.

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Siong Kang Lim **Peng Sung Loo**	Conceptualisation, study design, and supervision
Jet Sheng Yew **Hao Yee Richmond Chong** **Ming Kun Yew**	Data collection, methodology, and formal analysis
Siong Kang Lim **Jet Sheng Yew** **Jee Hock Lim**	Writing original draft preparation and literature review

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