

Using the Schleibinger Test System to Study the Restrained Drying Shrinkage Behavior of Lightweight Concrete

Ali Ahmed Aziz

Civil Engineering Department, University of Baghdad, Baghdad, Iraq
ali.aziz2301m@coeng.uobaghdad.ude.iq (corresponding author)

Ikram Faraoun Al-Mulla

Civil Engineering Department, University of Baghdad, Baghdad, Iraq
ikram.faroun@coeng.uobaghdad.edu.iq

Received: 15 July 2025 | Revised: 10 August 2025 | Accepted: 22 August 2025

Licensed under a CC-BY 4.0 license | Copyright (c) by the authors | DOI: <https://doi.org/10.48084/etasr.13414>

ABSTRACT

This paper examines the effect of different percentages of Polypropylene Fibers (PPFs) on the restrained shrinkage behavior (Schleibinger test) of Pumice Lightweight Concrete (LWC) at 0%, 0.5%, 1%, and 1.5%. The study investigates the changes in the timing for both vertical and horizontal restrained ring shrinkage tests. As shown in the experimental results, including PPF causes significant changes in the shrinkage response, especially at higher percentages. Vertical and horizontal strains display a pattern of periodic expansion and contraction at 1.5% PPF, indicating greater resistance to crack propagation due to the bridging effect of the fibers. Compared to the reference mix, fiber reinforcement alters the strain trend from primarily compressive to a balance between the cyclic responses, suggesting a delayed and more diffuse stress build-up during drying. This observation aligns with research on the microstructural role of PPF in managing the shrinkage cracking. The results show that 1.5% PPF not only decreases the early-age dimensional reduction in LWC, but also enhances the long-term dimensional stability. This behavior is crucial in applications where premature failure due to restrained shrinkage could occur. Based on these performance trends, optimized design scenarios are proposed to balance the workability and shrinkage control, which can help determine the ideal PPF content in future applications.

Keywords-polypropylene fibers; shrinkage strain; Schliebinger system restrained concrete; fiber-reinforced concrete; lightweight concrete; vertical strain; horizontal strain

I. INTRODUCTION

The development of modern building materials has brought significant attention to Fiber-Reinforced Concrete (FRC) due to its improved mechanical properties and durability. Among the different types of fibers, PPFs are widely studied because they enhance the concrete performance by reducing the permeability, controlling the cracking, and improving the tensile and flexural strength, as well as the long-term durability under varying environmental conditions [1, 2]. When used in LWC, PPF provides structural benefits by lowering the dead weight without compromising the strength. The addition of supplementary cementitious materials, silica fume, and pumice aggregates further refines the matrix density and durability [3]. These improvements are especially valuable in climates with high thermal gradients, where concrete is exposed to elevated temperatures and repeated environmental loading. Previous studies confirm that PPFs effectively control the crack formation, reduce the shrinkage, and enhance toughness. For example, authors in [4] reported that a 1% PPF dosage

improved the flexural and tensile performance while delaying the crack growth. Similarly, authors in [2] emphasized that the fiber volume must be optimized to balance the ductility and strength without excessively reducing the workability. The present study investigates the shrinkage behavior of PPF-reinforced LWC with respect to the compressive, flexural, splitting tensile strength, and restrained shrinkage. Four concrete mixes were prepared with varying fiber contents (0%, 0.5%, 1%, and 1.5%), and comprehensive testing was conducted in accordance with ASTM standards. The results provide insights into the role of PPFs in modifying the concrete performance across different curing ages. Finally, this research contributes to the development of sustainable, performance-optimized LWC systems and offers practical guidance for engineers and designers in selecting suitable materials and mix designs.

II. LITERATURE REVIEW

A. LWC and Shrinkage

LWC is often chosen for its low density and superior thermal insulation. However, its porous aggregate structure increases the risk of shrinkage and cracking [5]. Both autogenous and drying shrinkage are critical concerns in structural applications, making the effective mitigation measures essential.

B. PPFs in Concrete

Previous studies have highlighted the role of PPFs in controlling the shrinkage and cracking across different concrete types. For instance, authors in [6] showed that PPFs with circular cross-sections effectively reduced the plastic shrinkage cracks in mortar at very low dosages (0.1% by volume), with the advantage of maintaining the workability and minimizing the cost [15, 16]. In high-performance concrete, the addition of up to 0.5% PPFs, whether dry or pre-wetted, significantly reduced both the autogenous and total drying shrinkage compared to the standard mixes. Similarly, restrained-ring crack tests on lightweight aggregate concrete demonstrated that fiber dosages of up to 1% substantially reduced the shrinkage-induced cracking [7, 17]. In the case of Self-Compacting Concrete (SCC), the PPF incorporation led to a 40%–70% reduction in plastic shrinkage cracks when tested under both plate and ring conditions [8, 17, 18].

C. Fiber Dosage and Mechanical Properties

In [2], tensile and flexural strengths and durability were improved when using PPFs while free shrinkage reduced and workability was impaired above some fiber level. Equally, the experimental findings on lightweight foamed concrete showed a 28-day flexural enhancement of ~41.8% at 0.8 PPF.

D. Shrinkage in High-Performance PPF Concrete

Some studies suggested that a moderate amount of PPFs (4 kg/m³) struck a balance between the self-compacting flowability and mechanical property but did not provide much relevant discussion on shrinkage. It has also been found that the fiber-reinforced foamed concrete achieved an enhanced flexural strength and a reduced drying shrinkage for up to 180 days.

E. Summary and Research Gap

While previous studies have confirmed the effectiveness of PPFs in reducing shrinkage, most have focused on mortar or SCC. Limited research has examined the simultaneous behavior of vertical and horizontal shrinkage in PPF-reinforced LWC with varying fiber dosages (0.5%, 1%, and 1.5%). This study addresses this gap by conducting restrained shrinkage tests in both horizontal and vertical orientations [17], comparing the performance of different fiber contents under realistic curing conditions, and integrating the shrinkage findings with compressive, flexural, and tensile strength evaluations over a 90-day period.

III. METHODOLOGY

This study outlines the used materials, mix proportions, specimen preparation, and testing procedures for evaluating the

restrained shrinkage of fiber-reinforced LWC. The primary objective was to measure how varying PPF contents (0%, 0.1%, 0.5%, and 1.5%) influence the shrinkage strain over time using the restrained ring test method.

A. Materials

All concrete mixtures were prepared using the same materials to isolate the effect of the PPF dosage. Ordinary Portland Cement (OPC) conforming to [22] specifications was used as the primary binder, with silica fume added to enhance the matrix strength and reduce the permeability. Pumice served as the lightweight aggregate, lowering the concrete density while maintaining the structural strength. PPFs, consisting of short monofilament fibers with a tensile strength above 400 MPa, a length of 12 mm, and a specific gravity of 0.91, were incorporated at dosages of 0%, 0.5%, 1%, and 1.5% by volume. A polycarboxylate-based High-Range Water-Reducing Superplasticizer (HRWR) was included to maintain the workability at a low water-to-cement ratio, while potable tap water conforming to [19] specifications was used for mixing.

TABLE I. CEMENT CHEMICAL COMPOSITION AND MAIN COMPONENT

Oxide compositions	Weight (%)	Threshold of I.Q.S No. 5/2019
Lime (CaO)	60.35	----
Iron oxide (Fe ₂ O ₃)	4.16	----
Alumina (Al ₂ O ₃)	5.08	----
Silica (SiO ₂)	20.64	----
Insoluble residue (IR)	0.86	≤ (1.5)
Magnesia (MgO)	3.86	≤ (5)
Loss on Ignition (LOI)	3.21	≤ (4)
Sulfate (SO ₃)	2.67	SO ₃ ≤ 2.8 if C ₃ A > 3.5 SO ₃ ≤ 2.5 if C ₃ A ≤ 3.5
Main compounds of cement		
Tri-Calcium silicate (C ₃ S)	41.07	----
Dicalcium silicate (C ₂ S)	27.83	----
Tricalcium aluminate (C ₃ A)	6.43	----
Tetra-calcium aluminate – ferrite (C ₄ AF)	12.64	----
Oxide compositions	Weight (%)	Threshold of I.Q.S No. 5/2019
Lime (CaO)	60.35	----
Iron oxide (Fe ₂ O ₃)	4.16	----
Alumina(Al ₂ O ₃)	5.08	----
Silica (SiO ₂)	20.64	----
Insoluble residue (IR)	0.86	≤ (1.5)
Magnesia (MgO)	3.86	≤ (5)
Loss on Ignition (LOI)	3.21	≤ (4)
Sulfate (SO ₃)	2.67	SO ₃ ≤ 2.8 if C ₃ A > 3.5 SO ₃ ≤ 2.5 if C ₃ A ≤ 3.5

The fine aggregate comprised natural sand with a fineness modulus of 2.6. The sand met the requirements specified in [20] and was free from contaminants. The sand sieve grading and its main characteristics complied with those in [21]. Table III summarizes the physical characteristics and the chemical composition of the hired sand. Table II displays the grain size distribution of the sand.

TABLE II. POSSESSIONS OF SAND

Property	values	Boundaries [21]
Specific gravity	2.6	---
Absorption, %	0.72	---
Density (kg/m ³)	1580	---
Sulphate content, % (SO ₃)	0.343	Maximum 0.50%

TABLE III. SIEVE ANALYSIS

Sieve size(mm)	% Passing	Requirements of [21]
10	100.0	100
4.75	95.6	90-100
2.36	80.0	75-100
1.18	78.0	55-90
0.6	54.4	35-59
0.3	26.3	8-30
0.15	4.7	0-10
Finance modulus (FM)=2.61		

B. Mix Proportions

Four concrete mixes were prepared with varying fiber contents: Mix 1 (0% PPFs), Mix 2 (0.5% PPFs), Mix 3 (1% PPFs), and Mix 4 (1.5% PPFs). All mixes were designed with a constant water-to-cement ratio of 0.45. Silica fume was added at 10% of the cement weight to enhance the matrix performance, and a superplasticizer dosed at 1% of cement weight was included to maintain workability. The detailed mix proportions are presented in Table IV, while the properties of the superplasticizer are summarized in Table V.

TABLE IV. MIX PROPORTIONS AND DETAILS

Component	Control mix	0.5% PPF	1% PPF	1.5% PPF
Cement (kg/m ³)	450	450	450	450
Fine aggregate (kg/m ³)	775	775	775	775
Coarse aggregate (Pumice)(kg/m ³)	490	490	490	490
Water (kg/m ³)	166	166	166	166
Superplasticizer (% by weight of cement)	1	1	1	1
PPF (kg/m ³)	0	2	4	6

TABLE V. PROPERTIES OF THE POLYCARBOXYLATE ETHER (PCE) SUPERPLASTICIZER

Property	Value / description
Type	PCE
Appearance	Light brown/transparent liquid
Specific gravity at 25°C	1.08–1.12
pH range	5.0–7.0
Dosage (by binder weight)	1%
Solid content	30–40%

C. Mixing and Casting Procedure

A standard dry-to-wet mixing procedure was followed. First, cement, silica fume, and aggregates were blended for about 2 min. Water and superplasticizer were then added gradually to prevent clumping, while the PPFs were introduced slowly to ensure a uniform distribution within the mix. The prepared concrete was subsequently poured into restrained shrinkage ring molds fabricated in the civil engineering

laboratory of the University of Baghdad, in accordance with the specifications of [17].

D. Curing Conditions

After casting, the specimens were covered with plastic sheets, and the molds were removed after 24 h. The rings were then stored in a controlled environment at 23 ± 2 °C and $50\% \pm 4\%$ relative humidity. Further water curing was not applied to simulate the real-world conditions, such as drying, which leads to shrinkage.

E. Test Procedure

1) Restrained Shrinkage Test ([17])

This procedure assesses the cracking capability caused by the drying contraction under restrained surroundings. Strain gauges were fixed at the top surface to measure the axial strain and on the circumference of the ring to measure the hoop strain, as shown in Figure 1. The data acquisition systems were used to record the strain development over time, with key parameters including the time to crack, as well as the width and propagation of cracks where applicable.



Fig. 1. Strain gauge fixing on restrained concrete sample.

2) Visual Observation

The rings were visually inspected daily for surface cracking and the results were recorded, as depicted in Figure 2.



Fig. 2. Schliebinger system for restrained drying shrinkage testing.

F. Data Analysis

The results were obtained in the form of shrinkage strain versus time curves for each mix, followed by a comparative analysis between the reference mix and the fiber-reinforced mixes. The most significant performance measures were the percentage decrease in the maximum strain and the time to the crack initiation.

IV. RESULTS AND DISCUSSION

This research demonstrates the outcome of the constrained shrinkage tests of lightweight excursion with a PPF by volume. The shrinkage strain was determined in the horizontal and vertical directions as per the guidelines of [17], within 56 days. The development of strain in either of the two directions is graphically depicted. The trends, comparisons, and implications are also described in detail.

A. Reference Mix

The reference mix exhibited the highest level of restrained shrinkage in both orientations, with the horizontal and vertical strains reaching approximately 400 $\mu\epsilon$ by day 56, and cracks initiating relatively early, as shown in Figures 3 and 4. This mix also demonstrated high workability, with a slump value of about 120 mm. Since no fibers were included, the use of a superplasticizer was unnecessary, allowing the mix to be placed and compacted without resistance.

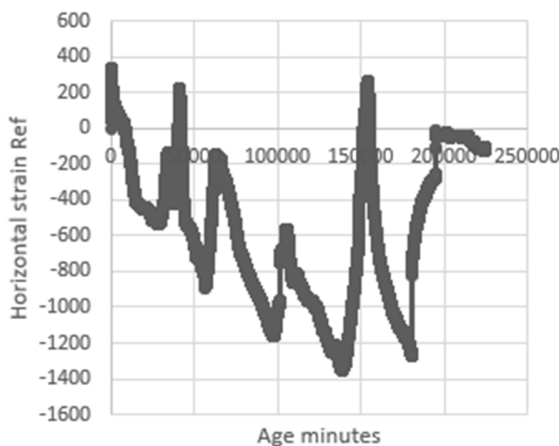


Fig. 3. Horizontal restrained shrinkage strain ($\mu\epsilon$) versus time for the reference mix (0% PPF).

The isotropic shrinkage behavior was observed, as indicated by the similar strain patterns in both directions in the absence of fibers. These results align with previous findings, according to which LWC without fibers is highly susceptible to early-age cracking [2].

B. Mix with 0.5% PPF

The addition of 0.5% PPFs resulted in a noticeable improvement, as displayed in Figures 5 and 6. The vertical and horizontal shrinkage decreased by 2.53% compared to the reference mix. The inclusion of 0.5% PPFs caused only a slight reduction in workability, with a slump value of about 100 mm. This minor decrease is likely due to the early interaction of

fibers within the mix, although the use of a superplasticizer helped to limit the effect.

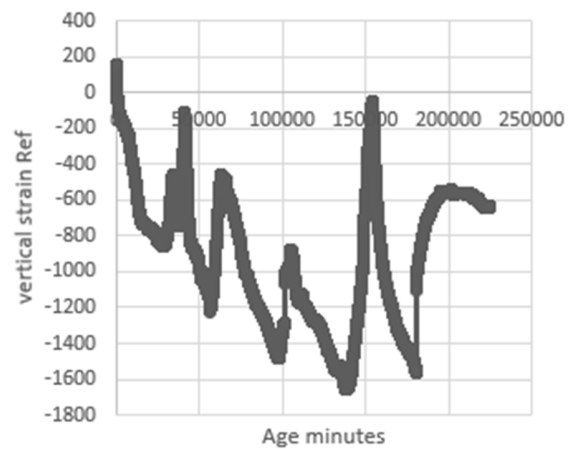


Fig. 4. Vertical restrained shrinkage strain ($\mu\epsilon$) versus time for the reference mix (0% PPF).

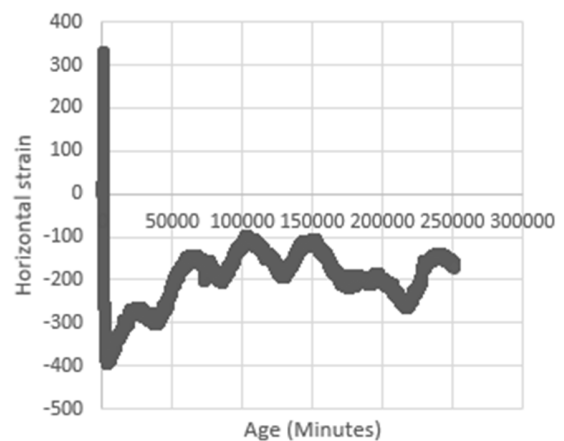


Fig. 5. Horizontal restrained shrinkage strain ($\mu\epsilon$) versus time for the 0.5% PPF mix.

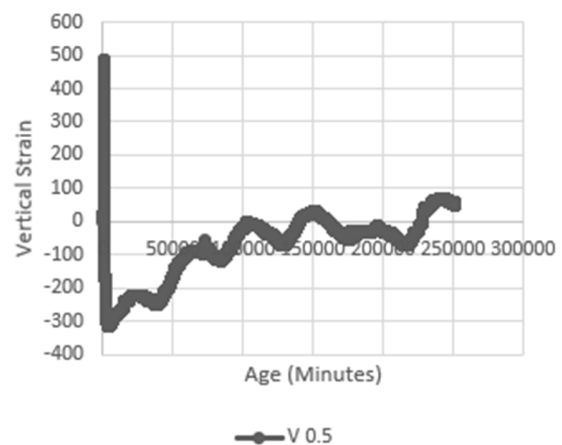


Fig. 6. Vertical restrained shrinkage strain ($\mu\epsilon$) versus time for the 0.5% PPF mix.

Such advantages can be attributed to the augmented fiber bridging and de-stressing, especially at low ages, and this follows the conclusions of [12].

C. Mix with 1% PPFs

The mix containing 1% PPFs showed a significant improvement in the shrinkage control compared to the reference mix. In the restrained shrinkage test, the horizontal strain was notably reduced, with a maximum value of about $330 \mu\epsilon$, while the vertical strain also decreased, though to a lesser extent. This indicates an improved resistance to early-age cracking, as the fibers helped redistribute the internal stress. Previous studies have similarly reported that 1% PPFs reduces both the free and restrained shrinkage, as well as the crack widths in concrete pavement slabs [13]. However, the workability declined further at this dosage, with slump being reduced to about 80 mm.

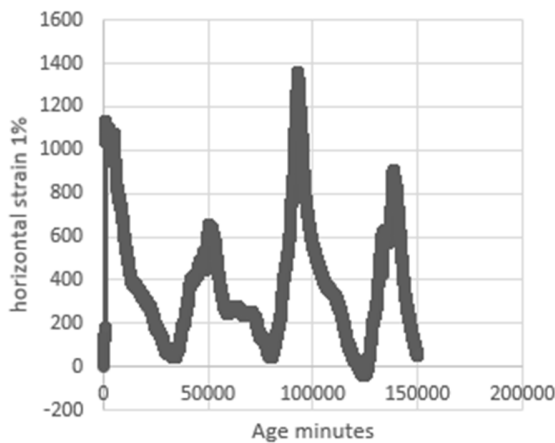


Fig. 7. Horizontal restrained shrinkage strain versus time for the 1% PPF mix.

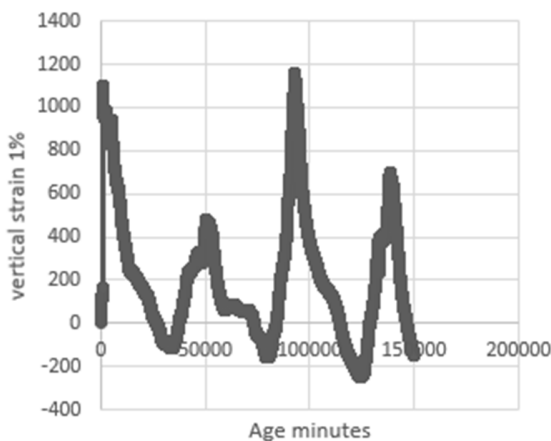


Fig. 8. Vertical restrained shrinkage strain versus time for the 1% PPF mix.

An intermediate level of fiber injection (1%), as shown in Figures 7 and 8) is useful to a) seal up the microcracks at the intersection of two plates, b) retard the propagation of cracks, as well as c) reduce the stress concentration caused by

shrinkage. This finding is congruent with the one in [1, 2], where it was indicated that stiff lightweight synthetic fibers, such as PPFs, alleviate the yarn-level tensile strains and improve the dimensional stability.

D. Mix with 1.5% PPFs

Figures 9 and 10 show that the 1.5% PPF mix exhibited distinct behavior in both the vertical and horizontal strain patterns compared to the reference mix and the other PPFs dosages (0.5% and 1%). This mix also had the lowest workability, with a slump of approximately 60 mm.

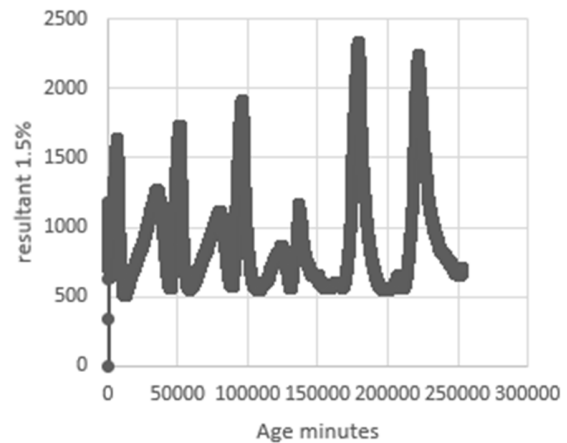


Fig. 9. Horizontal restrained shrinkage strain vs. time for the 1.5% PPF mix.

For the horizontal strain, the 1.5% PPF mix exhibited substantial values, with expansion reaching up to $+2000 \mu\epsilon$ and contraction approaching $-1200 \mu\epsilon$. This contrasts sharply with the reference mix, where the strains were predominantly negative and the contraction was dominant. The higher expansion values suggest that fibers contributed to the crack arrest and load redistribution in the horizontal direction as well. Compared to the 0.5% PPF mix, the 1.5% PPF mix showed smoother and more regular strain peaks, indicating a more uniform stress distribution under restrained shrinkage, both during and after crack initiation. As a result, the concrete matrix became tougher and more elastic, preventing the abrupt failure under tensile stress. The balanced cycles of expansion and contraction observed in the 1.5% PPF mix confirm the improved stress redistribution and microcrack bridging, supporting previous findings, according to which higher fiber volumes enhance the toughness and crack-bridging performance [14].

The vertical strain chart exhibits an oscillating pattern with multiple peaks and valleys, indicating that the concrete undergoes repeated cycles of expansion and contraction over time. The maximum vertical strains reach approximately $+1100 \mu\epsilon$ during expansion, while the contraction strains drop to around $-1300 \mu\epsilon$. The mix containing 1.5% PPF shows greater dimensional recovery during the expansion phases compared to the reference mix, even though both mixes experienced higher compressive strains (mostly negative values). This suggests that incorporating a higher volume of

fibers increases the internal restraint, enhancing the concrete’s resistance to crack propagation and deformation during the shrinkage cycles. The presence of multiple expansion stages also points to improved microcrack bridging, with fibers limiting the continuity and width of the microcracks caused by drying and thermal shrinkage. The positive strain values observed at higher levels of expansion can be interpreted as stress redistribution and gradual crack development, facilitated by the bridging effect of the additional fibers. Overall, the oscillating shrinkage–expansion behavior and enhanced microcrack bridging due to increased PPF content contribute to better dimensional recovery and stress redistribution in LWC under restrained shrinkage, complying with previous findings [7].

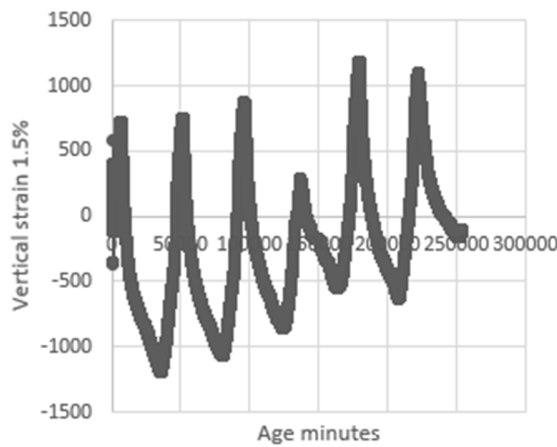


Fig. 10. Vertical restrained shrinkage strain versus time for the 1.5% PPF mix.

E. Comparative Discussion

The comparison of the strain of vertical and horizontal shrinkage behavior in the four concrete mixes, namely, Control (0% PPF), 0.5% PPF, 1% PPF, and 1.5% PPF, has given an important perspective about the use of PPF in reducing the deformation caused by shrinkage in LWC.

1) Vertical Strain Comparison

The vertical compressive strain over time was the highest in the reference mix (0% PPFs), with shrinkage reaching nearly $-1700 \mu\epsilon$, indicating an uncontrolled moisture loss and insufficient internal support to resist the early-age volume changes. In contrast, the 0.5% PPF mix showed a significant reduction in the compressive strain, ranging from -400 to $-300 \mu\epsilon$, though the amplitude of the strain variations was moderate, placing its shrinkage control in the middle of the group. The 1% PPF mix exhibited a more pronounced shift in behavior, which is consistent with previous studies [9, 10]. Despite the shrinkage, all mixes displayed cycles of expansion and contraction, suggesting that the fiber reinforcement improved the material’s ability to redistribute the internal stresses and prevent the localized cracking. Positive strain values occurred in several intervals, with maximum expansions reaching about $+1200 \mu\epsilon$, indicating temporary expansion phases. The 1.5% PPF mix continued this pattern but showed

more uniform oscillations with less severe shrinkage valleys. The strain fluctuations were more balanced around zero, reflecting an improved equilibrium between the expansion and shrinkage forces. This enhanced performance is attributed to the higher fiber content, which strengthens the tensile bridging, arrests the crack propagation, and increases the resistance to plastic shrinkage.

2) Horizontal Strain Comparison

A similar trend was observed for the horizontal strains. The reference mix experienced the greatest shrinkage, dropping to nearly $-1500 \mu\epsilon$. The 0.5% PPF mix showed a slight improvement, though shrinkage remained significant. The 1% PPF mix, however, displayed a different pattern, mirroring the vertical strain behavior with cyclical expansion and contraction, reaching over $+1300 \mu\epsilon$. Overall, the PPF mixes demonstrated the most restrained and symmetrical horizontal strain responses, with mean peak expansions around $+2000 \mu\epsilon$ and the lowest compressive strain values, significantly lower than those of the reference or 0.5% mixes. These results indicate that higher fiber contents enhance the multidimensional stability of concrete under restrained, repeated shrinkage cycles.

3) Overall Comparative Insights

Shrinkage Control Efficiency: The 1.5% PPF mix was the most effective in reducing the shrinkage in both the vertical and horizontal directions.

- Balance strain and Cyclic: Fiber-reinforced mixes, especially 1% and 1.5%, had an increased symmetry of strain behavior with the suggestion of delayed and distributed crack enlargement; this behavior is consistent with that reported in [11].
- Duplicity and Resilience of Material: A higher PPF content increased the duplicity as well as the resilience of the material due to the expansion cycles, which represented an improved recovery and ability to deal with the tensile stress. This finding complies with those in [12] when fibers are utilized to resist the impact loading.

TABLE VI. SUMMARY OF MAXIMUM VERTICAL AND HORIZONTAL STRAINS FOR ALL MIXES

PPF content (% by vol.)	Max vertical expansion ($\mu\epsilon$)	Max vertical contraction ($\mu\epsilon$)	Max horizontal expansion ($\mu\epsilon$)	Max horizontal contraction ($\mu\epsilon$)
0.0 (Ref.)	400	-1700	400	-1500
0.5	$\approx +400$	-400	$\approx +400$	≈ -300 to -400 (use -400)
1	1200	-300	1300	-100
1.5	1100	-1300	2000	-1200

These results are consistent with those of previous studies, which suggested that in LWC, higher fiber content enhances crack resistance through improved crack-bridging and more uniform stress redistribution [1, 2]. Consequently, a PPF volume fraction of 1.5% is proposed for structural applications where the long-term shrinkage could compromise durability.

Table VI summarizes the maximum expansions and contractions observed in both the vertical (axial) and horizontal (hoop) directions for all tested mixes. The positive values indicate temporary expansion, while the negative values represent contraction (shortening).

V. CONCLUSIONS

In this research, the influence of the addition of Polypropylene Fibers (PPFs) in different doses (0.5%, 1%, and 1.5%) to reduce the volume of shrinkage of Lightweight Concrete (LWC) was considered.

- The compliance results showed that the fiber content could be highly effective in reducing the dimensional shrinkage and improving the probability because of the consistent observation of the vertical strains and horizons during the period.
- There was evidence of significant shrinkage in the vertical and horizontal directions associated with the control mix (0% PPF), which indicated the susceptibility of the lightweight-spun concrete to early-age shrinkage and drying shrinkage.
- With the addition of 0.5% PPFs, a slight improvement in the strain behavior, and a lowered magnitude of strain, the strain rate was also reduced. These advantages were also increased with the dose of 1% PPFs that, in turn, demonstrated balanced expansion and contraction stages, which means better redistribution of the internal stresses.
- It was at 1.5% PPF content that the improvement was the most remarkable. The data indicated weaker compressive strain variations and higher expansion periods in the vertical and horizontal directions. This implies that the elevated volume of fibers not only postpones the crack initiation, but also boosts the post-crack ductility. Fibers are considered a bridging agent that limits the microcrack development and enhances what is called the overall resilience of the concrete matrix against restrained conditions.
- PPF in LWC causes a considerable increase in the ability of the latter to resist the shrinkage-induced deformation. Among all tested dosages, the strained behavior was improved the most with 1.5% PPF, making this amount effective for applications requiring high crack resistance and dimensional stability.

DATA AVAILABILITY

Data will be made available on request.

REFERENCES

- [1] A. A. J. Ghanim, M. Amin, A. M. Zeyad, B. A. Tayeh, I. S. Agwa, and Y. Elsakhawy, "Effect of polypropylene and glass fiber on properties of lightweight concrete exposed to high temperature," *Advances in concrete construction*, vol. 15, no. 3, pp. 179–190, Jan. 2023, <https://doi.org/10.12989/acc.2023.15.3.179>.
- [2] M. Amin, B. A. Tayeh, and I. saad agwa, "Investigating the mechanical and microstructure properties of fibre-reinforced lightweight concrete under elevated temperatures," *Case Studies in Construction Materials*, vol. 13, Dec. 2020, Art. no. e00459, <https://doi.org/10.1016/j.cscm.2020.e00459>.
- [3] R. Dollaiah, R. Venu, and P. R. Hampannaver, "Effect of Fiber on the Performance of Self-compacting Concrete with Fly Ash, GGBS, and Alccofine as Cementitious Materials – NanoWorld Journal," *NanoWorld Journal*, vol. 9, pp. 500–509, Mar. 2023, <https://doi.org/10.17756/nwj.2023-s3-092>.
- [4] J. Ahmad, F. Aslam, R. Martínez-García, J. de Prado-Gil, N. Abbas, and M. Hechmi EI Ouni, "Mechanical performance of concrete reinforced with polypropylene fibers (PPFs)," *Journal of Engineered Fibers and Fabrics*, vol. 16, Jan. 2021, Art. no. 15589250211060399, <https://doi.org/10.1177/15589250211060399>.
- [5] P. Zhang and Q. Li, "Experimental Study on Shrinkage Properties of Cement-stabilized Macadam Reinforced with Polypropylene Fiber," *Journal of Reinforced Plastics and Composites*, vol. 29, no. 12, pp. 1851–1860, Jun. 2010, <https://doi.org/10.1177/0731684409337336>.
- [6] Y. Ma, M. Tan, and K. Wu, "Effect of different geometric polypropylene fibers on plastic shrinkage cracking of cement mortars," *Materials and Structures*, vol. 35, no. 3, pp. 165–169, Apr. 2002, <https://doi.org/10.1007/BF02533585>.
- [7] S. B. Daneti, T.-H. Wee, and T. s/o Thangayah, "Effect of polypropylene fibres on the shrinkage cracking behaviour of lightweight concrete," *Magazine of Concrete Research*, vol. 63, no. 11, pp. 871–881, Nov. 2011, <https://doi.org/10.1680/macr.2011.63.11.871>.
- [8] J. R. Pereira, J. B. L. P. e Silva, L. A. Gachet, A. C. dos Santos, and R. C. C. Lintz, "Evaluation of the Addition of Polypropylene (PP) Fibers in Self-compacting Concrete (SCC) to Control Cracking and Plastic Shrinkage Between Different Methods," *Materials Research*, vol. 26, 2023, Art. no. e20220567, <https://doi.org/10.1590/1980-5373-MR-2022-0567>.
- [9] I. F. Al-Mulla, A. S. Al-Ameeri, A. S. Al-Rihimy, and T. S. Al-Attar, "Elasticity and Load-Displacement Behavior of Engineered Cementitious Composites produced with Different Polymeric Fibers," *Engineering, Technology & Applied Science Research*, vol. 14, no. 1, pp. 13026–13032, Feb. 2024, <https://doi.org/10.48084/etasr.6731>.
- [10] I. F. Al-Mulla, A. S. Al-Ameeri, and T. S. Al-Attar, "Long-Term Drying Shrinkage Strain of Engineered Cementitious Composite Concrete Contains Polymeric Fibers," *Journal of Engineering*, vol. 2024, no. 1, 2024, Art. no. 8887928, <https://doi.org/10.1155/2024/8887928>.
- [11] I. F. Al-Mulla and A. S. Al-Rihimy, "The Effect of the Hydrophilic and Hydrophobic Behavior of Polymeric Fibers on Some Properties of Reactive Powder Concrete," *Engineering, Technology & Applied Science Research*, vol. 15, no. 2, pp. 21691–21694, Apr. 2025, <https://doi.org/10.48084/etasr.10157>.
- [12] J. Abd and I. K. Ahmed, "The Effect of Low Velocity Impact Loading on Self-Compacting Concrete Reinforced with Carbon Fiber Reinforced Polymers," *Engineering, Technology & Applied Science Research*, vol. 11, no. 5, pp. 7689–7694, Oct. 2021, <https://doi.org/10.48084/etasr.4419>.
- [13] M. Gholami, F. Moghadas Nejad, and A. M. Ramezani-pour, "Increasing the Length of Concrete Pavement Slabs Using Shrinkage Reducing Admixture and Polypropylene Fiber," *International Journal of Concrete Structures and Materials*, vol. 18, no. 1, Feb. 2024, Art. no. 9, <https://doi.org/10.1186/s40069-023-00647-8>.
- [14] T. Aly, J. G. Sanjayan, and F. Collins, "Effect of polypropylene fibers on shrinkage and cracking of concretes," *Materials and Structures*, vol. 41, no. 10, pp. 1741–1753, Dec. 2008, <https://doi.org/10.1617/s11527-008-9361-2>.
- [15] *ACI PRC-544.1R-96: Report on Fiber Reinforced Concrete*. USA: American Concrete Institute, 2023.
- [16] *ASTM C1116/C1116M-23 Standard Specification for Fiber-Reinforced Concrete*. USA: ASTM International, 2023.
- [17] *ASTM C1581-04 Standard Test Method for Determining Age at Cracking and Induced Tensile Stress Characteristics of Mortar and Concrete under Restrained Shrinkage*. USA: ASTM International, 2010.
- [18] *ASTM C1579-21 Standard Test Method for Evaluating Plastic Shrinkage Cracking of Restrained Fiber Reinforced Concrete (Using a Steel Form Insert)*. USA: ASTM International, 2021.
- [19] *ASTM C1602/C1602M-22 Standard Specification for Mixing Water Used in the Production of Hydraulic Cement Concrete*. USA: ASTM International, 2022.

- [20] *ASTM C33/C33M-18 Standard Specification for Concrete Aggregates.*
USA: ASTM International, 2023.
- [21] *Iraqi Specification IOS 45-1984.* Iraq: Iraqi Standard Specification,
1984.
- [22] *ASTM C150/C150M-24 Standard Specification for Portland Cement.*
USA: ASTM International, 2024.