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Mechanical and Volumetric Changes of Sustainable Lightweight Fibrous Concrete with Fine Recycled Aggregate and Silica Fume

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Abstract: This study presents an experimental program aimed at producing durable and sustainable lightweight concrete using lightweight expanded clay aggregate (LECA) as coarse aggregate, With the completely replacement of fine aggregate with recycled concrete aggregate. To enhance the quality of the cementitious matrix and its long-term behavior, 15% silica fume and 1% steel fiber were incorporated into the mixtures. Five mixtures were prepared with a water to cement ratio of 0.4: NFA-based mix and four modified mixes with the addition of silica fume, steel fibers or a combination of both. Mechanical properties and durability were evaluated through several tests including compression strength, tensile strength, dry density, water absorption, dry shrinkage and wet expansion which were evaluated at two curing ages of 28 and 90 days. The findings indicate that the use of RFA as a full replacement for NFA led to a noticeable reduction (about 15%) in strength at 28 days. The use of steel fibers improved the splitting tensile strength by up to 20% compared to the control mixture. The combined effect of blending SL and MSF demonstrated a substantial enhancement in the mechanical performance. The compressive and tensile strengths increased by approximately 13% and 33%, respectively, at 90 days. Using silica fume together with steel fiber effectively reduced the elevated water absorption typically observed in mixture containing RFA. In addition, the blend showed reduced volumetric change, with reductions of 26% in shrinkage and 41% in expansion. The results showed the effectiveness of the use of pozzolan materials and fibers in the development of SLWC using recycled aggregates while improving durability and strength.

Keywords: Lightweight concrete, Durability, Recycled fine aggregate, Shrinkage, Expansion

Introduction

Concrete, composed mainly of cement, aggregate and water, is the commonly utilized building material in the world because of its superior compressive capacity and good durability that make it suitable for various construction applications. However, the widespread reliance on the production and use of concrete on a global scale has led to the emergence of serious environmental problems, the most important of which is the significant depletion of natural resources, especially natural aggregates, in addition to the carbon emissions resulting from the manufacture of cement, which are among the most prominent factors causing the rise in the concentration of greenhouse gases in the atmosphere. Considering these environmental issues, the engineering and research community in the construction sector has moved towards adopting more sustainable alternative solutions and materials that seek to reduce the environmental impact of concrete without compromising its mechanical behavior and required structural performance(Selman & Abbas, 2022; Karthik et al., 2021). It is worth mentioning that one of the most essential factor in achieving sustainability in concrete construction is durability. Durable concrete maintains its mechanical and physical properties under various environmental exposure conditions such as moisture, salts, chemical attack. By resisting such deterioration mechanisms, durable concrete limits the attract of

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harmful substances, prevents reinforcement corrosion, and minimises structural degradation (Bejan et al., 2020). This long-term performance reduces maintenance needs, conserves resources, and extends service life, making durability a key indicator of a concrete's sustainability.

The development of lightweight concrete (LWC) represents one of the most promising approaches in the design of sustainable concrete, as it contributes to reducing the self-weight of structures, allowing for the design of smaller sections and lighter foundations, as well as improving their seismic performance. Its light-weight also facilitates the handling and transportation of soft concrete during pouring processes (Xie et al., 2019). Typically, Lightweight concrete (LWC) is manufactured using light -weight aggregates such as expanded clay aggregate (LECA), which is manufactured by firing the clay at high heat inside rotary kilns, causing it to expand and form a porous cellular structure that gives it low weight and good thermal insulation properties. (Murugan et al., 2023;Nahhab & Abo Dhaheer, 2024).

LECA offers advantages including low density, thermal insulation, and reasonable mechanical strength. However, its high porosity may increase permeability and reduce long-term durability unless the concrete matrix is modified (Shaker, 2022,Karthik et al., 2022)Besides reducing the concrete's self-weight, improving its performance in terms of sustainability also includes replacing natural aggregates with recycled materials. One of the practical and suitable alternatives to natural sand is a recycled fine aggregate (RFA), extracted from old demolition and concrete wastes (Tabsh & Alhoubi, 2022; Gao et al., 2021).

The use of recycled fine aggregates contributes to supporting sustainability by reducing the gathering of demolition waste in waste areas and reducing the depletion of raw materials. However, unless its characteristics are enhanced with appropriate additions or modification of the material, this type of aggregate's high porosity, low density, and weak interfacial zone (ITZ) might result in excessive water absorption, high shrinkage, and low mechanical resistance(Zhou et al., 2021). Supplementary cementitious materials (SCMs), such silica fume, have been widely utilized to get over those limitations. It improves hydration in concrete by reacting with calcium hydroxide to produce more calcium silicate hydrate (C–S–H) gel (Nadim et al., 2024;Kumar, et al., 2023). Additionally, silica fume improves cohesion and lessens bleeding, particularly in aggregate mixtures that are lightweight and recycled.(Nazarimofrad et al., 2017). It significantly enhances the strength and durability of lightweight concrete by increasing its density and reducing its porosity. Silica fume is very fine particles densify the micro-pores within the concrete paste, leading to a denser structure, which improves compressive strength and overall mechanical performance(Bhavana et al., 2015).

Moreover, it contributes to reducing shrinkage and cracking in lightweight concrete, thereby improving its overall durability and performance (Sajedi & Shafigh, 2012). Alongside the use of silica fume, the incorporation of steel fibers has been reported to improve the mechanical and durability performance of both normal and LWC mixes (Mohamed et al., 2023). When added in appropriate proportions of steel fibers led to an increase in tensile strength, reduced the width and spread of cracks, improved concrete behavior after cracking, and reduced volumetric changes (Motar & Awad, 2023; Liao et al., 2025). The simultaneous combination of steel fiber and silica fumes improves the overall performance of the concrete by reducing permeability, achieving better control of volume changes, and enhancing its resistance to cracking and chemical attacks.(Motar & Awad, 2023).

Research Significance

Although numerous researchers have investigated the individual effects of recycled aggregates, silica fumes, and steel fibres on the behaviour of lightweight leca-based concrete mixtures, has not been thoroughly explored the combined effects of the above materials, especially in terms of long-term durability and strength. In order to overcome this limitation, this study aims to develop lightweight concrete that meets both strength and durability requirements. Special focus is given to evaluating the combined impact of the above-mentioned materials on long-term compressive and tensile strength, water absorption, shrinkage, and expansion.

Experimental Program

Materials

Type I Ordinary Portland Cement (OPC) conforming to the Iraqi Specification No. 5/**2019** (IQS 5, 2019) was used in all concrete mixtures. The chemical composition and physical characteristics of this type of cement are shown in Tables 1 and 2, respectively. The coarse aggregate employed was LECA, which has a nominal maximum size of 10 mm, a water absorption capacity of approximately 12%, and a bulk density of around 700 kg/m³. Its grading complied with ASTM C330 requirements (ASTM C330, 2017). Two categories of fine aggregate were used: Normal fine aggregate (NFA) and recycled fine aggregate (RFA). The RFA was obtained by crushing old hardend concrete specimens and sieving the resulting material using a 4.75 mm sieve. Both types met the Iraqi standards for aggregate quality (IQS No. 45, 1984). Tables 3 and 4 show the grading of fine and coarse aggregate. The silica fume used was light grey densified powder with a specific gravity of 2.25 and SiO_2 of 90% and conforming to the Standard Specification (ASTM International C 1240, 2003). It was employed to partially substitute cement to enhance the microstructure and long-term durability of the prepared LWC mixes. To ensure adequate workability while limiting water content, superplasticizer admixture was used in dosages ranging from 0.5% to 1.0% by weight of cement. The admixture complied with the ASTM C494-04 standard for chemical admixtures materials (ASTM C494/C494M, 2017). Steel fibres were also incorporated into the concrete at a volume fraction of 1%, with a length-to-diameter ratio of 65. The materials utilized in this research are presented in Figure 1.

Steel fiber

Silica fume

LECA

Recycled fine aggregates (RFA)

Figure 1. Materials used in this study

Table 1. Chemical properties of cement

Compound composition	Test results	Limits of IQS No.5:2019
CaO%	62.810	-------
SiO2%	21.952	-------
Al2O3%	4.748	-------
Fe2O3%	3.211	--------
MgO%	2.526	≤ 5%
SO3%	1.883	≤ 2.5% if C3A <3. 5% ≤ 2.8% if C3A > 3.5%
Loss on Ignition%	2.832	≤ 4%
Insoluble residue%	0.897	≤ 1.5%
L.S.F	0.882	0.66 – 1.02
Main compounds		
C3S%	45.377	--------
C2S%	28.704	--------
C3A%	7.149	---------
C4AF%	9771	---------

Table 2. Physical properties of cement

Test		Results	Limits of the IQS No. 5/2019
Finesse in (Blaine) m^2/kg		291	≥ 280
Initial setting time (minutes)		69	≥ 45
Final setting time (hours)		5:24	≤ 10
Compressive strength	3 days (MPa)	21.15	≥ 20
	7 days (MPa)	45.06	≥ 42.5

Table 3. Sieve analysis of the NFA and RFA

Size (mm)	Cumulative passing %		Limit of IQS No.45/1984
	NFA	RFA	Zone 1
10	100.0	100	100
4.75	95.2	99	90-100
2.36	85.4	74	60-95
1.18	55.2	45	30-70
0.6	20.6	28	15-34
0.3	8.8	20	5-20
0.15	4.2	8	0-10

Table 4. Sieve analysis of LECA

Size (mm)	Cumulative passing %	Limits of ASTM C330-2017
12.5	100	100
9.5	100	80-100
4.75	28	5-40
2.36	5.2	0-20

Concrete Mix Proportioning, Casting, and Testing

Five lightweight concrete (LWC) mixtures were prepared using a fixed water-to-cement ratio (w/c) of 0.4, following the guidelines of ACI Committee 211.2-98 (ACI 211, 1998). Tables 5 and 6 present the composition and proportions of the mixes used in this study. The reference mix contained natural fine aggregate (NFA), whereas the remaining four mixes incorporated recycled fine aggregate (RFA). All aggregates were utilized in a surface-saturated dry (SSD) condition. Moulds were lubricated with oil before casting prevent adhesion of the concrete to the internal surfaces. The fresh mix was poured into the molds and compacting by vibrating table. All samples (except those designated for shrinkage testing) were cured in water under controlled temperature conditions for periods of 28 and 90 days. For each mix, six cube specimens (100×100×100 mm) were cast for compressive strength testing in accordance with European Committee (BS EN 12390-3, 2009)Six cylindrical specimens (200×100 mm) were made for splitting tensile strength testing following European Committee (BS EN 12390-6, 2009) In addition, three cube specimens (150×150×150 mm) were cast per mix to determine water absorption in accordance with ASTM C642 ASTM C642, 2013) . To determine dry density, three cube specimens (150×150×150 mm) were produced in accordance with ASTM C642 (ASTM C642, 2013).

Table 5. Details of the prepared mixes

Mix	Details
NFA	LECA+0 Recycled fine aggregate
RFA (Ref.)	LECA+100 Recycled fine aggregate (Reference)
RFA+SL	LECA+100 Recycled fine aggregate+15% Silica fume
RFA+SF	LECA+100 Recycled fine aggregate+1%steel fiber
RFA+SL+SF	LECA+100 Recycled fine aggregate+15% Silica fume+ 1%steel fiber

To evaluate volumetric changes, six prism specimens (50×50×200 mm) were prepared for each mix to evaluate drying shrinkage and wet expansion as per ASTM C157 (ASTM C157, 2003) .A digital comparator length device (Figure 3) was used to monitor length changes during the shrinkage and expansion tests. Both tests were performed at different curing intervals: 3, 7, 14, 28, 42, 56, 73, and 90 days. Each reported result corresponds to the main value obtained from three specimen for each mix.

Table 6. Mix proportion of the prepared LWC mixes (kg/m^3)

Mix details	Cement	Silica fume	Water	w/c	SP	NFA	RFA	LECA	MSF
NFA	450	0	175	0.4	2.5	735	0	434	0
RFA (Ref.)	450	0	175	0.4	3	0	629	434	0
RFA+SL	384	49	175	0.4	3	0	629	434	0
RFA+1SF	450	0	175	0.4	5	0	618	428	78
RFA+SL+1SF	384	49	175	0.4	5	0	618	428	78

Figure 2. Volume changes test

Figure 3. A digital comparator length device

Results and Discussion

Compressive Strength (Fcu)

Table 7 and Figures 4 and 5 illustrate the compressive strength development of the five LWC mixes at curing ages of 28 and 90 days. The results show clear variations in mechanical performance based on the inclusion of supplementary materials and aggregate type. At 28 days, NFA-based LWC, which contained natural fine aggregates, achieved a compressive strength of 32.8 MPa. In contrast, replacing NFA with 100% RFA resulted in a significant reducing in compressive strength as it dropped to 27.9 MPa which represents an approximate 15% reduction in the relative mix made from NFA. This reduction is linked to a weakened ITZ and increased porosity associated with recycled aggregate particle's (Nahhab & Abo Dhaheer, 2024).

Incorporating 15% silica fume into the RFA mixes enhanced compressive strength to 30.1 MPa, a 7.9% improvement over the RFA mix. This enhancement is attributed to the high pozzolanic activity of silica fume that consumes calcium hydroxide and forms extra C–S–H gel(Zhang et al., 2020). Additional improvement was observed in the RFA+SF mix, which incorporated 1% micro steel fibers. The compressive strength of this mixture was 34.7 MPa, an increase of 24.4% compared to the reference mixture, and this improvement is due to steel fiber's ability to restrain cracking and control their growth within the concrete matrix, which contributes to the redistribution of stresses more efficiently. combined effect of matrix densification by silica fume and crack controlling by steel fibers (Köksal et al., 2008) .

At 90 days, as a result of enhanced internal microstructure over time, a signifcant increase in compressive strength was noted for all concrete mixtures. The compressive strength of the mixture containing natural fine aggregates (NFA) was 35.3 MPa, while the mixture containing recycled fine aggregates (RFA) recorded a strength of 29.1 MPa, a decrease of 18% compared to the reference mixture. This reduction is mainly linked to the high pore content of the RFA and the weak interfacial transition zone (ITZ) between the old mortar and the new paste. On the other hand, incorporating of 15% silica fume in the RFA+SL mix resulted in a notable improvement in the compressive strength to 33.5 MPa, an increase of 15.1% compared to the reference mixture, due to the active silica reaction (pozzolan reaction) and the increased density of the concrete matrix resulting from the presence of silica fume.

This enhancement can be linked to the pozzolanic reactivity of silica fume, which becomes increasingly active at later curing ages, resulting in the generation of additional calcium silicate hydrate (C–S–H) gel(Mortazavi & Majlessi, 2013), i.e., densifies the concrete matrix and improves particle packing between paste and aggregate. The RFA+SF mix reached 37 MPa, a 27.1% increase over the reference. It can obviously be seen from Table 3 and Figure 5 that the highest strength was achieved in the RFA+SL+SF mix, which combined both silica fume and steel fibres. This mix reached 40 MPa, exceeding the reference strength by 37.5%. This is no doubt attributed to the effect of pozzolanic action of silica fume from one hand, and the reinforcing role of steel fibres, on the other hand They in turn, enhance the microstructure, reduce porosity, and increase the load-carrying capacity of the tested LWC mixes.

Table 7. Mechanical properties of the tested mixes

Mix designation	**Slump, Mm**	**Fcu at 28 days**	**Fst at 28 days**	**Fcu at 90 days**	**Fst at 90 days**	**Absorption % (at 28 days)**	**Absorption % (at 28 days)**	**Dry density, kg/m³**
NFA	110	32.8	2.93	35.3	3.05	3.77	2.94	1724
RFA (Ref.)	95	27.9	2.45	29.1	2.57	5.54	4.57	1620
RFA+SL	105	30.1	2.7	33.5	2.94	4.57	3.39	1608
RFA+1 %SF	90	34.7	3.61	37	3.83	4.83	3.74	1694
RFA+SL+1% SF	95	35.4	3.64	40	4.05	3.89	3.15	1674

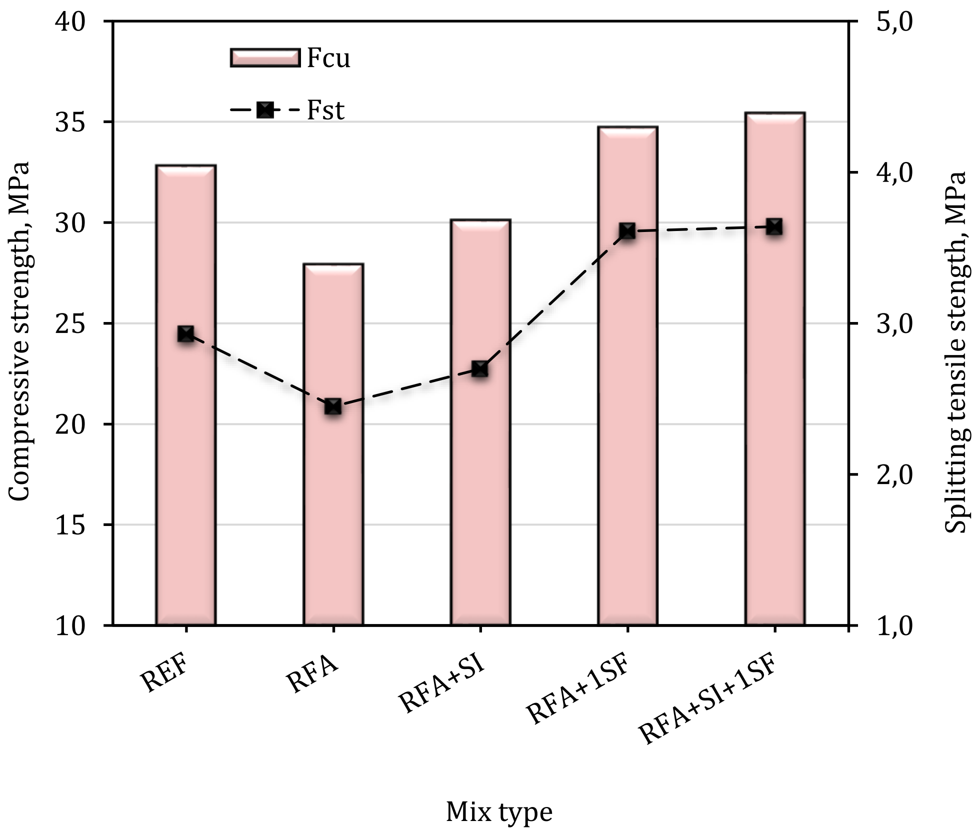

Figure 4. mechanical properties of LWC at 28 days

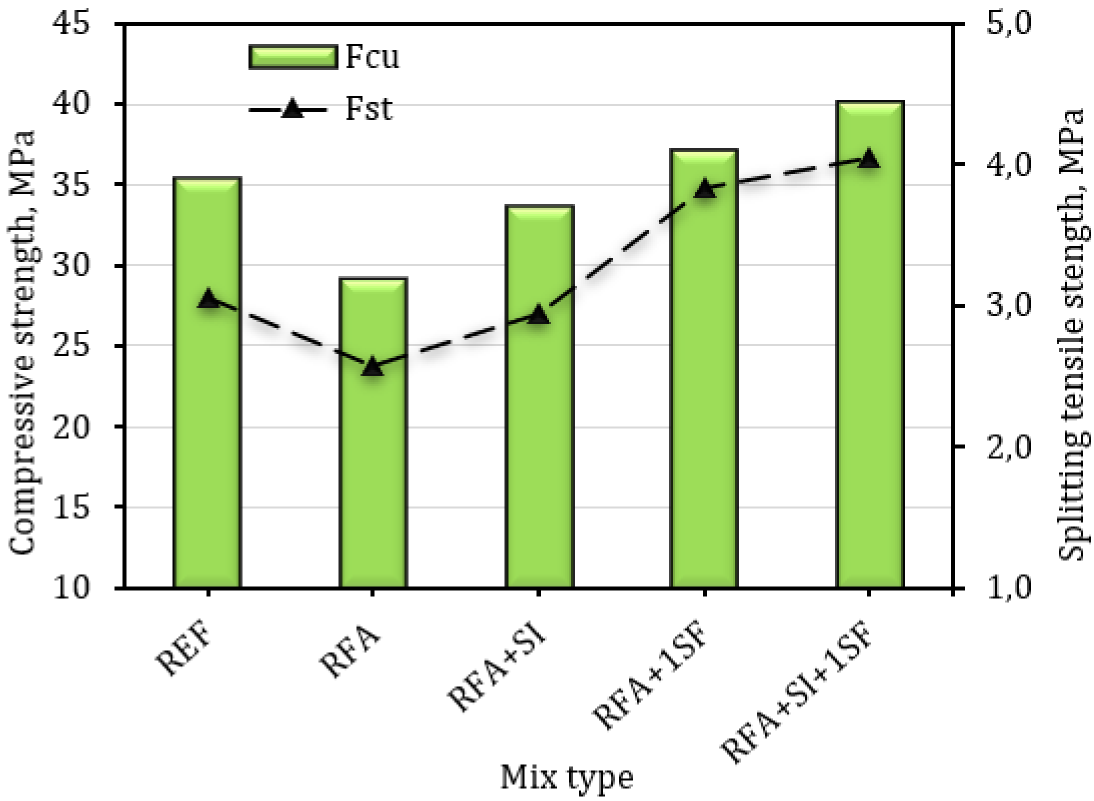

Figure 5. Mechanical properties of LWC at 90 days

Splitting Tensile Strength (Fst)

Table 7 and Figures 4 and 5 present the enhancment of splitting tensile strength (fst) for the five LWC mixes at ages of 28 and 90 days. The results reveal clear variations in fst depending on aggregate type and the inclusion of silica fume and steel fibres. At 28 days, the mix containing NFA achieved fst of 2.93 MPa. In contrast, the mix incorporating 100% RFA exhibited a significant reduction (16%) compared to the NFA-concrete. The decrease in splitting tensile strength in the RFA mixture is attributed to the high porosity of RFA and the poor interconnection quality between the old mortar and the new cement paste, resulting in a weakening of the interficial zone (ITZ) and a reduction in the ability of concrete to withstand severe stresses(Ju et al., 2019).

The incorprating of 15% silica fume into RFA mix led to a noticeable enhancement in splitting tensile strength, improved to 2.70 MPa showing a 10.2% increase relative to the RFA mixture.this increase is attributed to the strong pozzolanic behavior of silica fume, which contributes to improving the microstructure and enhancing the bond between the aggregate particles and the cementitious matrix(Leung et al., 2016). According to table 3 and figure 4 a clear improvement is observed in the performance of the RFA + SF mix containing 1% of the micro steel fiber (MSF), where the splitting tensile strength (Fst) increased to 3.61 MPa, recording an increase of 47.3% compared to the reference mixture. this enhancement can be due to the fiber bridging mechanism which effectively increases the resistance to crack propagation by restricting crack width and delaying their growth under tensile stress (Zamri et al., 2024). The hybrid mix showed superior mechanical behavior at 28 days of age with a splitting tensile strength of 3.64 MPa an increase of 48.6% compared to the reference mixture, reflecting a clear synergistic effect between the two additives.

At 90 days of age, all concrete mixtures showed further improvement in siplitting tensile strength as a result of the continuous rehydration process and the formation of secondary rehydration products that increase the density of the microstructure. The tensile strength of the NFA mixture was 3.05 MPa while the RFA mixture achieved a value of 2.57 MPa confirming the continued impact of the recycled aggregate on tensile properties with age. RFA+SL and RFA+SF mixes recorded 3.83 MPa, an increase of 14.4% and 49.0%, respectively, compared to the reference mix. The RFA+SL+SF hybrid had the highest splitting tensile strength at 90 days of 4.05 MPa, an increase of 57.6% compared to the reference mix.This enhancement in performance is due to the synergistic effect between silica fume which improves matrix density and iron fibers which enhance the bonding mechanism through cracks and increase tensile strength(Köksal et al., 2008).

Absorption

Table 7 and Figure 6 illustrate the absorption percentages of the five LWC mixes at curing ages of 28 and 90 days. The results clearly demonstrate the influnce of aggregate type and the inclusion of silica fume and steel fibre on the porosity characteristics of LWC. At 28 days of age, the mixture containing natural fine aggregate had the lowest absorption value of 3.77% showing a relatively dense internal structure with low porosity. In contrast, a mixture containing 100% recycled fine aggregate (RFA) exhibited a notably higher absorption rate of 5.54% because of the porous nature and rough surface texture of the recycled aggregate particles residual mortar and micro cracks in the recycled aggregate may have increased the water absorption (Jasim et al., 2024). From the other side, the addition of 15% silica fume (RFA+SL mix) reduced the absorption to 4.57% that silica fume provided more effective pore refinement (Wu et al., 2024). The mix containing 1% steel fibres (RFA+SF) recorded a slightly lower reduction in absorption (with a value of 4.83%). This suggests that although steel fibres are efficient at limiting crack growth, their direct influence on improvement of the capillary (Shaker, 2022). Moreover, the **inclusion of** both silica fume and steel fibres (mix RFA+SL+SF), demonstrated a noticeable improvement, with absorption of 3.89%, reaching the absorption level of the NFA-based mix. This can be justified by the fact that silica fume improves the matrix density and the steel fibres minimize microcrack propagation.

When it comes to 90-day test results, all the tested mixes experienced further reductions in absorption, reflecting continuing hydration and matrix enhancement with age, as clearly pronounced in Table 4 and Figure 6. The absorption of the mix NFA decreased to 2.94%, while the RFA mix remained the highest at 4.57%. The RFA+SL and RFA+SF mixes recorded values of 3.39% and 3.74%, respectively. The lowest absorption at this age was observed in the RFA+SL+SF mix, 3.15% confirming the long-term effectiveness of combining pozzolanic and fibrous enhancements in reducing permeability (Arel & Shaikh, 2018).

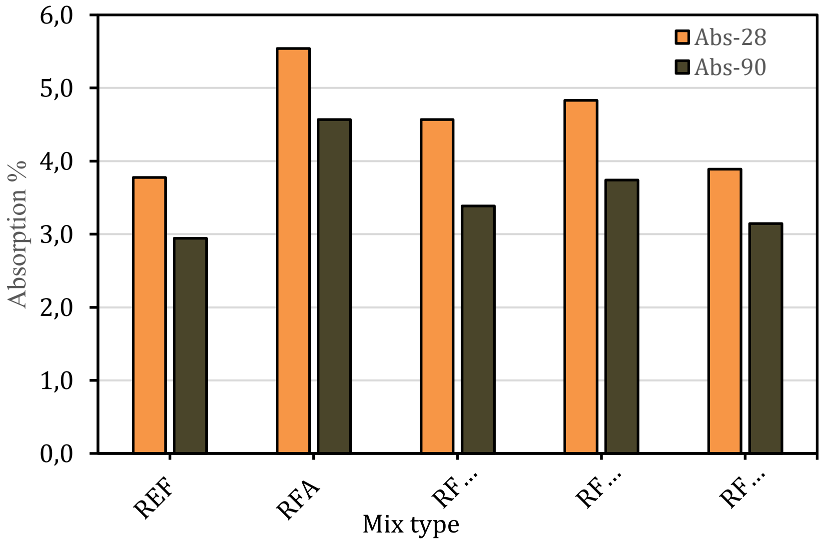

Figure 6. Absorption test results

Dry Density

The dry density results shown in Table 7 and Figure 7 clearly illustrate how aggregate substitution and the presence of complementary additives affect the density of lightweight concrete (LWC) mixtures. The reference mixture containing natural fine aggregates (NFA) recorded the highest dry density value of 1724 kg/m³. The relatively higher specific weight of NFA and its lower porosity result in better particle packing and reduce the size of the internal voids within the concrete matrix(Nahhab & Abo Dhaheer, 2024). In this context an additional slight decrease in density was observed when the RFA+SL mixture containing 15% silica fumes was used, recording 1608 kg/m³. This is because concrete mixtures containing silica fume in part rather than part cement are usually less dense than mixtures containing cement alone. This difference is because the specific weight of Silica fume (2.25) is lower than that of regular Portland cement (3.15) so replacing a portion of the cement with Silica fume reduces the total mass per unit volume of the mixture(Al-Rekabi et al., 2023).

In contrast the addition of 1% iron fibers by volume in the RFA + 1% SF mixture resulted in a significant increase in density to 1694 kg/m³ (Hameed, 2013). This increase is directly due to the high specific weight of the steel fiber which in addition to providing mechanical strength to the concrete also contributes to increased particle interference and improved packing within the concrete matrix(Nahhab & Abo Dhaheer, 2024). Additionally, mix cast with both silica fume and steel fibres (RFA+SL+1%SF) produced an intermediate density value of 1674 kg/m³.

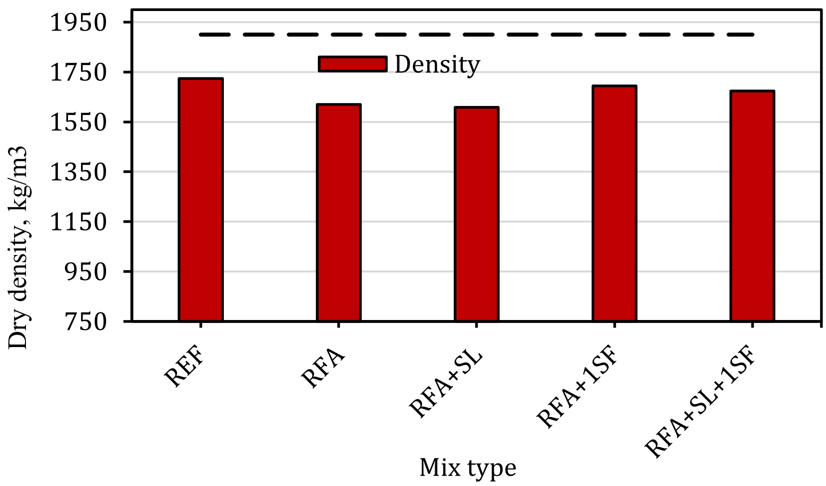

Figure 7. Dry density test results

Volume Change

Table 8. Shrinkage values (micro-strain) of concrete mixes up to 90 days

Mix designation	Age (day)						
	14	21	28	42	56	73	90
NFA	274	358	456	594	623	661	677
RFA (Ref.)	257	393	540	633	684	750	781
RFA+SL	302	416	523	610	653	714	727
RFA+1SF	312	383	453	520	563	578	603
RFA+SL+1SF	295	367	426	498	567	584	591

Shrinkage

The drying shrinkage values measured up to 90 days for all lightweight concrete mixtures are summarized in Table 8 and Figures 8-9. Drying shrinkage strain increased progressively with age for all the cast mixes. At the age of 90 days the mix containing NFA recorded a shrinkage strain of 677 microstrain. The full substitution of NFA with RFA noticeably increased the shrinkage to 781 microstrain, reflecting an obvious increase of approximately 15%. This increase is in agreement with previous studies which show that recycled fine aggregates (RFA) due to their porous nature and weak ITZ lead to increased water absorption and moisture loss, which aggravated volumetric contraction during drying (Khatib, 2005).

Interestingly, the incorporation of 15% silica fume (RFA+SL) resulted in a modest reduction in drying shrinkage reaching 727 micro strain at 90 days compared to the RFA mix. Although silica fume improves the concrete microstructure reducing porosity and enhancing durability its impact on drying shrinkage was relatively minor.This behavior can be attributed to the fine particle size and the resulting larger surface area which slightly increased the rate of moisture loss and consequntly caused aminor rise in early age drying shrinkage(Li & Cui, 2012).The most significant improvement in shrinkage behavior was pronounced in mixes containing steel fibres.

The inclusion of 1% steel fibers (RFA+1%SF) reduced shrinkage significantly to 603 microstrain, a 22.8% reduction compared to the RFA mix (without fibres). This result is no doubt associated with the ability of steel fibers to mitigate shrinkage through mechanical interlocking and reinforcement, which restrains internal deformation and, in turn, reduces volumetric changes (Domagala, 2011,Nahhab & Ketab, 2020). The combined incorporation of silica fume and steel fibres (RFA+SL+1%SF) achieved the lowest shrinkage strain, recording only 591 microstrain at 90 days, representing a 24 % reduction relative to the RFA reference mix.

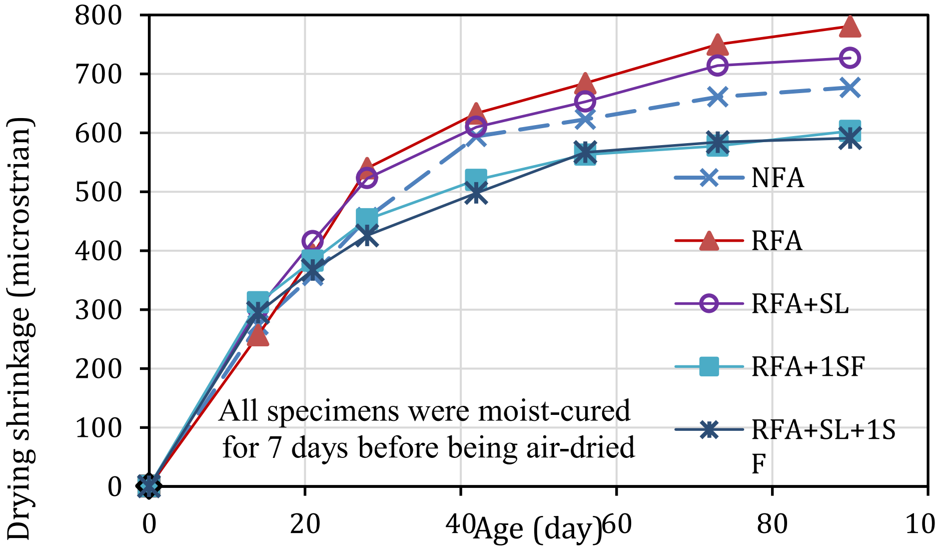

Figure 8. Drying shrinkage of the tested specimens with age

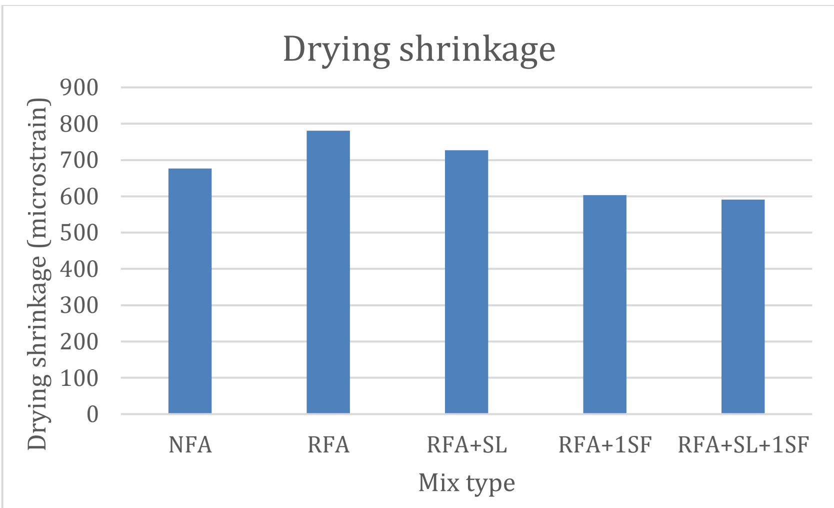

Figure 9. Drying shrinkage at 90 days age

Expansion Test Results

The expansion test results of the LWC mixes measured up to 90 days are summarized in Table 9 and graphically presented in Figures 10 and 11. It is evident that there is a progressive increase in expansion strains of all mixes with curing age, which is due to the continuous absorption of water during the curing period. At 90 days, the mix containing NFA achieved an expansion strain of 483 microstrain. When fully replacing NFA with RFA, the expansion increased significantly, reaching 576 microstrain, which represents a 19 % increase. The reason behind that might be related to the inherent porosity and higher water absorption capacity of RFA particles. Besides, the presence of adhered mortar and microcracks on RFA surfaces further increases volume changes.

The findings also revealed that the incorporation of 15% silica fume (mix RFA+SL) significantly reduced expansion compared to the reference mix , limiting the expansion to 535 microstrain at 90 days. The noted reduction is primarily due to the pozzolanic reaction of silica fumes. This reaction significantly densifies the microstructure of the cementitious matrix and leads to reducing the overall permeability and restriction volumetric expansions (Nadim et al., 2024). The addition of 1% steel fibers into the LWC mix RFA+1%SF resulted in a noticeable reduction in expansion, which reached 408 microstrain at 90 days, representing approximately 29 % lower expansion compared to the reference mix (with RFA).

This proves the effectiveness of steel fibers in controlling volume changes through crack bridging and uniform stress distribution across the concrete matrix. The findings also revealed that the decrease in specimen expansion was much more pronounced in mix incorporating both silica fumes and steel fibers (RFA+SL+1%SF). This mix recorded the lowest expansion, with an observed value of 392 microstrain at 90 days. This represents a reduction of 32 % relative to the RFA-based mix.

Table 9. Expansion values (micro strain) of concrete mixes up to 90 days

Mix designation	Age (day) 3	7	14	21	28	42	56	73	90
NFA	54	107	197	245	325	420	448	489	483
RFA (Ref.)	86	135	193	321	422	478	547	568	576
RFA+SL	77	115	234	307	377	469	499	512	535
RFA+1SF	59	106	220	281	296	362	376	402	408
RFA+SL+1SF	68	114	225	265	288	320	361	370	392

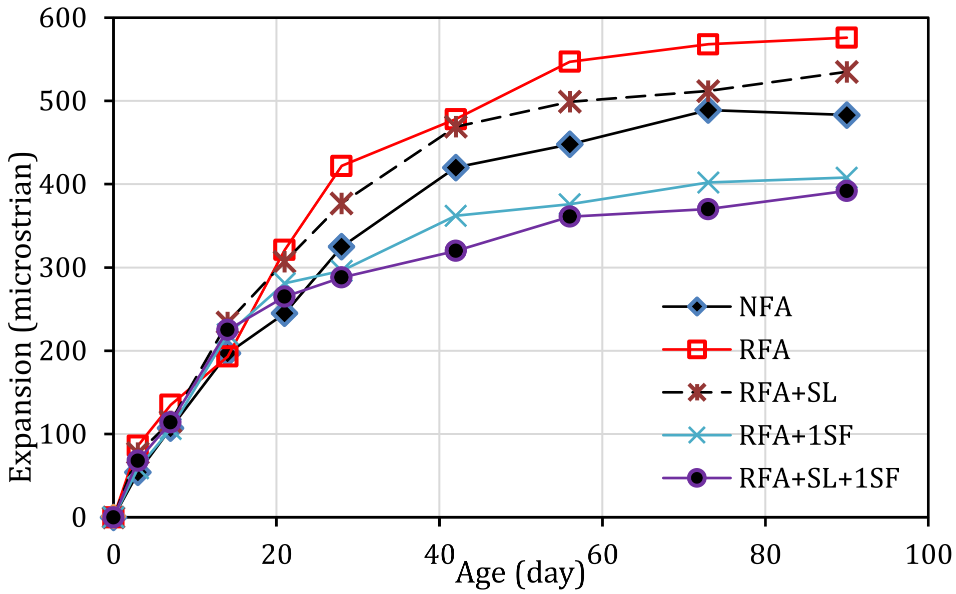

Figure 10. Expansion of the tested specimens with age

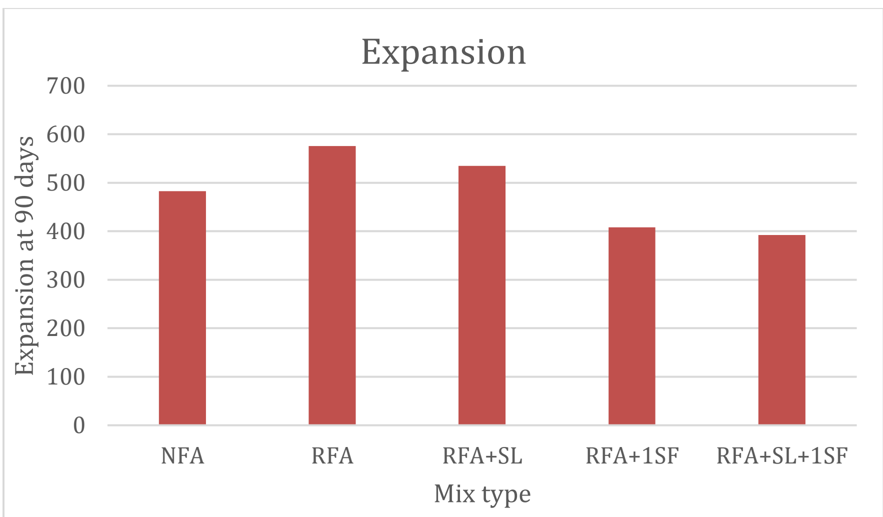

Figure 11. Expansion at 90 days age

Conclusion

1. 15% reduction in compressive strength and tensile strength by 16% with increased drying shrinkage by about 11% and volumetric expansion by about 24% when total replacement of NFA with RFA
2. The use of silica fume compensated for the lack of strength and improved the microstructure of the matrix and led to a decrease in the volumetric changes of lightweight mixtures
3. The addition of iron fibres by 1% of the volume improved the compression and splitting tensile strength and restricted the contraction by about 26% and expansion by about 41%.
4. The combined use of steel fibre and silica fume gave us the optimal performance, achieving the highest compressive and splitting tensile strength, the lowest absorption and the least volume changes.
5. All mixtures, even containing steel fibres, gave us a dry density of less than 1850 kg/m3, thus compliant with the requirements of standard density and the best mechanical performance and durability. Incorporating silica fume and steel fibres presents a feasible and sustainable approach for producing RFA-based LWC mixes with enhanced mechanical behaviour, durability, and dimensional stability.

Recommendations

Exposure to aggressive environments: Investigating the resistance of optimized mixes to sulfate attack, chloride penetration, carbonation, alkali–silica reaction. This will help assess the applicability of these concretes in marine, industrial, and cold climate conditions. Advanced microstructural characterization: Employing more sophisticated techniques such as X-ray computed tomography (XCT), and anther techniques to better quantify pore connectivity, hydration, and the evolution of the ITZ over time.

Scientific Ethics Declaration

* The authors affirm that they bear full scientific, ethical, and legal responsibility for the content of this article published in EPSTEM journal.

Conflict of Interest

* All authors state that they have no competing interests relevant to the content of this study.

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