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High-Strength Lightweight Silica Fume Concrete with Fine Recycled Aggregate and Steel Fiber

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Abstract: Sustainable lightweight concrete presents a promising solution for reducing environmental pollution caused by construction and demolition waste. This study focuses on developing high-strength lightweight concrete (HSLWC) using lightweight expanded clay aggregate (LECA) as coarse aggregate and fully replacing natural fine aggregate (NFA) with recycled fine aggregate (RFA). To enhance performance of the produced mixes, 15% silica fume and varying contents of micro steel fibers (0.5% and 1%) were incorporated. Seven concrete mixtures were prepared with a low water to cement (w/c) ratio of 0.25 and tested at 28 days to evaluate slump flow, compressive strength, splitting tensile strength, density, and water absorption. The results revealed that using 100% RFA reduced compressive strength from 54.5 MPa to 45.7 MPa and splitting tensile strength from 4.67 MPa to 4.03 MPa. However, the inclusion of 1% steel fibers compensated for this reduction, raising compressive strength to 55.1 MPa and splitting tensile strength to 5.89 MPa. Further enhancement was observed when silica fume was combined with steel fibers, resulting in a maximum compressive strength of 58.1 MPa and a splitting tensile strength of 6.11 MPa. These values exceeded those of the reference mix made with NFA. The combined use of silica fume and steel fibers led to the most effective improvement, producing sustainable HSLWC with superior mechanical performance, reduced water absorption, acceptable workability, and structural lightweight density.

Keywords: Sustainable materials, Lightweight concrete, Recycled fine aggregate, High-strength concrete

Introduction

With growing concern over environmental impact, the construction industry is adopting more sustainable and eco-friendly materials to help limit emissions and reduce the strain on natural resources Neville, A. M. (2011) . Within this context, lightweight concrete (LWC) has appeared as a key material, thanks to its ability to reduce structural self-weight, lower foundation loads, and offer economic and practical advantages with achieving adequate strength and durability. Structural lightweight aggregate (LWA) concrete is defined according to ASTM C330 (C330, 2017) and American Concrete Institute ACI 213R-03 as a type of concrete with a density ranging between 1200 and 1920 kg/m³ and a compressive strength of no less than 17 MPa at 28 days. It may be composed entirely of lightweight constituents or a combination of light and normal weight materials. One of the most suitable materials for producing LWC is expanded clay aggregate (LECA), which is considered favored for its low specific gravity, stable porous structure, and excellent thermal and sound insulation characteristics. Research has shown that LECA provides adequate mechanical strength and good bonding with cement paste, leading to a well-balanced concrete matrix in terms of mechanical and structural performance (Ghanem & Awad, 2024). However, to enhance sustainability and reduce the depletion of natural aggregate sources, efforts have increasingly focused on replacing natural aggregates (NA) with recycled alternatives such as recycled fine aggregates (RFA) sourced from demolition concrete waste. Despite the environmental benefits of RFA, its use presents several challenges. The presence of adhered old mortar and the resulting weak interfacial transition zone (ITZ) between the RFA particles and the fresh paste can cause higher porosity and increased microcracking, leading to reduced mechanical

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strength and durability (Nahhab & Dhaheer, 2024). To address these issues, researchers have proposed the use of supplementary cementitious materials such as silica fume (SF). Silica fume is a highly reactive pozzolanic material that interacts with calcium hydroxide to form additional calcium silicate hydrate, enhancing the microstructure of the paste. Studies confirm that replacing up to 15% of cement with SF can improve both compressive and tensile strengths while significantly reducing water absorption, particularly in mixes with low water-to-cement ratios (i.e., high strength concrete) . (Ibrahim & Aziz, 2015;Mohamed et al., 2023)

In parallel, steel fibers have demonstrated considerable effectiveness, in reinforcing both normal and high strength concrete (HSC), by bridging microcracks, enhancing ductility, and improving the tensile and flexural strength of the matrix. When incorporated at 1% of the concrete volume, steel fibres contribute to better stress distribution and improved post-cracking performance, allowing concrete to withstand loads beyond initial cracking.(Hameed, 2013) . The crucial parameter in designing HSC is the water to cement (w/c) ratio. Lowering this ratio is known to improve mechanical resistance by reducing porosity and increasing matrix density in the mix. However, such mixes often require high-range water-reducing admixtures (HRWR) to ensure adequate workability and prevent problems like poor compaction or segregation(Mehdy, 2023) .

An examination of previous studies indicates that, to the best of the researcher's knowledge, that limited studies have sufficiently emphasized the combined effect of using recycled fine aggregate (RFA), lightweight expanded clay aggregate (LECA), silica fume, and steel fibres on high-strength lightweight concrete (HSLWC), particularly under a low water-to-cement (w/c) ratio. Consequently, this study aims to develop HSLWC using LECA and RFA with a w/c ratio of 0.25. To compensate for the potential limitations of RFA, 15% silica fumes and up to 1% steel fibres were incorporated. The study examines several critical properties including compressive and splitting tensile strengths, water absorption, density, and workability.

Experimental Program

Materials

(A): Recycled fine aggregate

(B): LECA

(C): Silica fume

(D): Steel fiber

Figure 1. Materials used in this study

Type I Ordinary Portland Cement (OPC) conforming to the Iraqi Specification (IQS 5 2019). It was used in all concrete mixtures. The coarse aggregate used is LECA (Figure 1-B), 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 types of fine aggregates were incorporated in the mixtures: Natural Fine Aggregate (NFA) and Recycled Fine Aggregate (RFA), Figure 1-A. The sieve analysis of the two types is illustrated in Table 1. The RFA was obtained by crushing previously cast concrete cube specimens using a crushing machine and sieving the resulting material through a 4.75 mm sieve. Both types met the Iraqi standards for aggregate quality (IQS 45, 1984).

Silica fume (Figure 1-C) was a light grey, densified powder with a specific gravity of 2.25 and SiO_2 of 90% and conforming to the standard specification ASTM C 1240, (2003) ,was used as a partial replacement of cement to enhance the microstructure of the prepared LWC mixes. To ensure adequate workability while limiting water content, a high-range water-reducing admixture (HRWR) was used in dosages ranging from 0.5% to 1.0% by weight of binder. The admixture complied with the ASTM C494-04 standard for chemical admixtures (ASTM C494-04). Micro steel fibers were also incorporated into the HSLWC mixes at a volume fraction (vf) of 0.5 % and 1%, with a length-to-diameter ratio (aspect ratio) of 0.65 (Figure 1-D).

Table 1. 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

Concrete Mix Proportioning, Casting and Testing

Seven HSLWC mixes were designed with a w/c of 0.25, following the ACI Committee 211.2-98 (Committee, 1998). Tables 2 and 3 present the composition and proportions of the mixes used in this study. The reference mix contained natural fine aggregate (NFA), whereas the remaining six mixes incorporated RFA. All aggregates were used in a saturated surface-dry (SSD) condition. Moulds were pre-coated with oil prior to casting to prevent adhesion of the concrete to the internal surfaces. The fresh concrete was placed into the moulds and compacted using a vibrating table (Figure 3).

Figure 3. Compaction of the tested mixes

All specimens were cured in water under controlled temperature conditions for periods of 28 days (Figure 4). For each mix, 3 cube specimens (100×100×100 mm) were cast for compressive strength testing in accordance with European Committee for Standardization EN 12390-3. (2019). 3 cylindrical specimens (200×100 mm) were prepared for splitting tensile strength testing following European Committee for Standardization. EN 12390-6 (2022). In addition, 3 cube specimens (150×150×150 mm) were cast per-mix to determine water absorption in accordance with ASTM C642. To determine the dry density, the same cube specimens used for absorption test, were utilized in accordance with ASTM C642 .reported values represent the average of three samples for each mix.

Figure 4. Curing of the prepared HSLWC

Table 2. Designation of the tested 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+0.5%SF	LECA+100 Recycled fine aggregate+0.5 %steel fiber
RFA+1%SF	LECA+100 Recycled fine aggregate+1%steel fiber
RFA+SL+0.5%SF	LECA+100 Recycled fine aggregate+15% Silica fume+ 0.5%steel fiber
RFA+SL+1%SF	LECA+100 Recycled fine aggregate+15% Silica fume+ 1%steel fiber

Table 3. Mix proportion lightweight concretes (Kg/m3)

Mix details	Cement	SL	Water	w/c	SP	NFA	RFA	LECA	MSF
NFA	650	0	157	0.25	4.4	615	0	434	0
RFA (Ref.)	650	0	157	0.25	5.2	0	526	434	0
RFA+SL	553	72	157	0.25	4.84	0	526	434	0
RFA+0.5%SF	650	0	157	0.25	5.75	0	521	432	39
RFA+1%SF	650	0	157	0.25	6.5	0	515	428	78
RFA+SL+ 0.5%SF	533	72	157	0.25	5.35	0	521	432	39
RFA+SL+1%SF	553	72	157	0.25	6.1	0	515	428	78

Results and Discussion

Slump Test

Table 4 and Figure 5 illustrate the slump behavior of the seven LWC mixes. The NFA-based LWC, incorporating natural fine aggregates, achieved a slump of 90 mm, providing a reference level of workability considered adequate for lightweight concrete. In contrast, replacing the natural sand with 100% recycled fine aggregate (RFA) resulted in a 105 mm, when 15% silica fume was added to the recycled aggregate mix (RFA+SL), the slump further improved to 110 mm. This improvment can be attributed to the filler effect and enhanced paste cohesiveness associated with silica fume, which enhances lubrication among particles and increases flowability. However, the addition of 0.5% steel fibers to the RFA+0.5%SF mix reduced the slump to 80 mm. This reduction in workability is attributed to the physical obstruction caused by fibers that restrict the movement of fresh concrete and increase internal friction (Yang et al., 2022). Similarly, the mixes cast with MSF achieved a slump of 80-90 mm, indicating a moderate slump compared with the reference RFA mix. This suggests that while steel fibers negatively affect slump by restricting flow (due to interlocking effects workability), a HRWR can help balance workability to the acceptable level as the NFA reference mix.

Table 4. Mechanical properties of the tested mixes

Mix designation	Compressive strength (Fcu)		Splitting strength (Fst)		Slump (mm)	Absorption %	Dry density kg/m^3
	Fcu, MPa	Increase, % of Ref.	Fcu MPa	Increase, % of Ref.			
NFA	54.5	+16	4.67	+14	90	2.58	1835
RFA (Ref.)	45.7	0	4.03	0	105	4.22	1726
RFA+SL	49.9	+9.2	4.33	+7.4	110	3.81	1721
RFA+ 0.5 %SF	53.7	+17.5	5.21	+29.3	80	4.05	1760
RFA+ 1%SF	55.1	+20.6	5.89	+46.2	85	3.92	1790
RFA+SL+ 0.5 %SF	56	+22.5	5.8	+43.9	90	3.6	1748
RFA+SL+ 1 %SF	58.1	+27.1	6.11	+51.6	80	3.16	1775

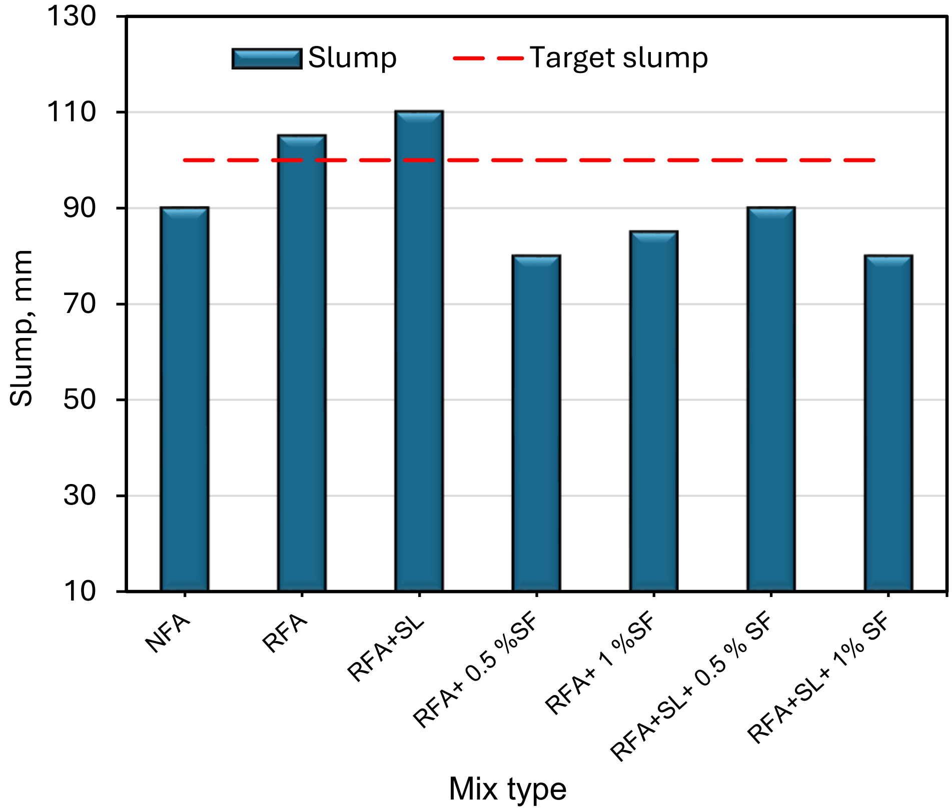

Figure 5. Result of the slump test

Compressive Strength

Table 4 and Figure 6 present the compressive strength development of the seven HSLWC mixes at 28 days. The mix made of NFA recorded a compressive strength of 54.5 MPa. In contrast, full replacement of NFA with 100% RFA resulted in a reduced compressive strength of 45.7 MPa, which means approximately 16% lower than the NFA mix. This decline is mainly due to the higher porosity and weaker ITZ associated with RFA, along with the presence of residual mortar, which typically weakens bond quality in concrete matrix (Motwani et al., 2013). However, incorporating 15% silica fume into the RFA-based mix (RFA+SL) increased the compressive strength to 49.9 MPa, reflecting a 9.2% improvement over the control mix. This enhancement is associated with the pozzolanic activity of silica fume, which improves the pore structure, thereby, enhancing matrix density and aggregate paste bonding (Mortazavi & Majlessi, 2013).

The inclusion of 0.5% steel fibres (RFA+0.5%SF) raised the compressive strength to 53.7 MPa, which is a 17.5% gain over the RFA-based mixes. Increasing the steel fibre content to 1% (RFA+1%SF) further improved the strength to 55.1 MPa, gaining 20.6% above the control mix. These improvements are attributed to the crack-bridging action of fibres, which delays crack propagation, enhances stress redistribution, and contributes to greater toughness (Wu et al., 2024a). From the test results of this experimental study, the most pronounced improvements were observed in the mixes combining both silica fume and steel fibres. The RFA+SL+0.5%SF mix reached 56 MPa, while the RFA+SL+1%SF mix achieved the highest compressive strength of 58.1 MPa, which represents respective improvements of 22.5% and 27.1% respectively, compared to control mix. This no doubt arises from the combined benefits of matrix densification by silica fume and crack control by steel fibres (Green Concrete Aggregated Book Kryvenko Kolisnychenko, 2023), (Bejan et al., 2020).

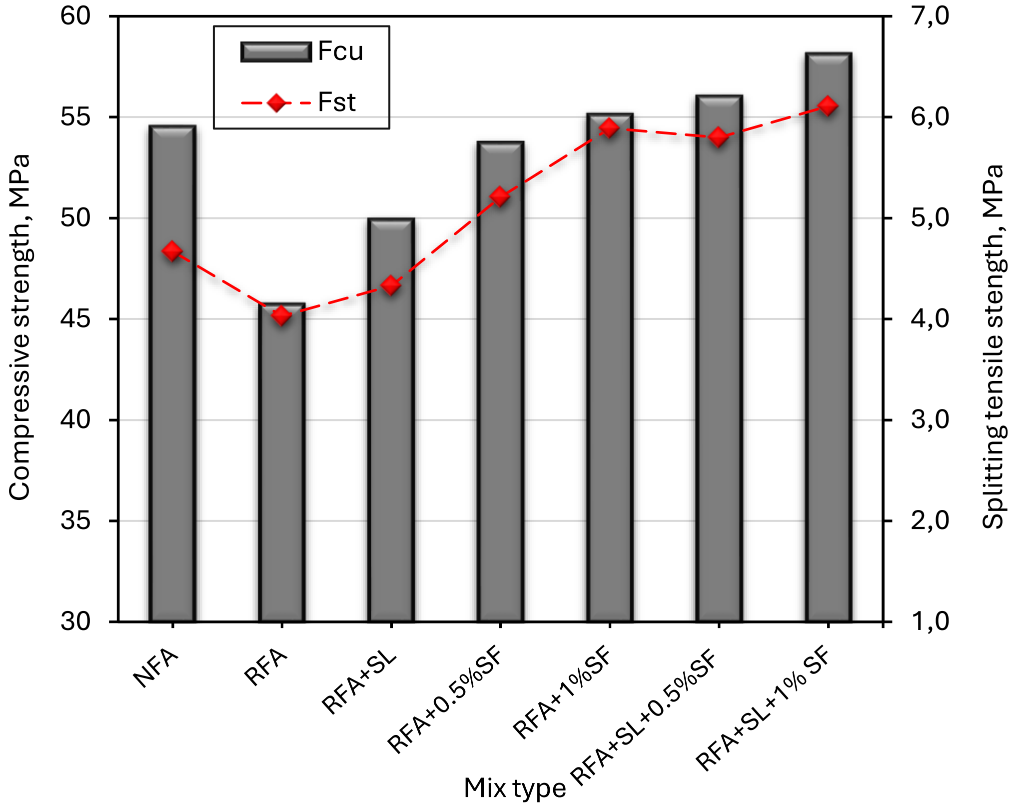

Figure 6. Results of mechanical properties of the tested mixes

Splitting Tensile Strength

The test results of splitting tensile strength (fst) across the tested HSLWC mixes are illustrated in Table 4 and Figure 6. The data indicate that fst is significantly influenced by the type of fine aggregate and the incorporation of silica fume and steel fibres. The mix with only NFA yielded the highest value of 4.67 MPa. However, when NFA was totally replaced with RFA, fst dropped to 4.03 MPa. This reduction is primarily related to the higher porosity and lower bonding quality in the used RFA (Lee & Choi, 2013) .On the other hand, introducing 15% silica fume into the RFA mix (RFA+SL) improved the fst to 4.33 MPa, recording a 7.4% improvement over the control mix. This enhancement is attributed to ability of silica fume to densify the microstructure and strengthen the bonding between paste and aggregate (Nadim et al., 2024).

Apparently from Figure 6, the addition of steel fibres produced more significant results. A vf of 0.5% MSF (RFA+0.5%SF) increases the splitting tensile strength to 5.21 MPa (29.3%) increase compared to the RFA-based mix. Increasing the fibre content to 1% (mix RFA+1%SF) further enhanced fst to 5.89 MPa, reflecting a 46.2% improvement. The higher fibre volume promotes better crack control and energy absorption, especially under tensile loading (Al-Rekabi et al., 2023). Moreover, combinations of silica fume and steel fibres demonstrated even superior development, as the RFA+SL+0.5%SF and RFA+SL+1%SF mixes achieved fst of 5.8 MPa and 6.11

MPa, corresponding to improvements of 43.9% and 51.6% over the reference mix, respectively. This is justified by matrix densification and crack-bridging of silica fume and steel fibers, respectively, in the cast HSLWC mixes.

Water Absorption

The water absorption test results of the HSLWC mixes at 28 days were presented in Table 4 and Figure 7. The results demonstrate that the choice of aggregate type and the incorporation of silica fume and steel fibers have a significant impact on the permeability behavior of concrete. Among all the tested mixes, NFA-based HSLWC mix exhibited the lowest water absorption of 2.58%, indicating a dense and well-packed microstructure with a stable ITZ. In contrast, the mix incorporating 100% RFA exhibited a noticeably higher absorption of 4.22%. This substantial rise is attributed to the higher porosity, residual adhered mortar, and irregular surface texture of RFA particles (Ju et al., 2019) . However, the addition of 15% silica fume (RFA+SL mix) reduced the absorption to 3.81%.

Furthermore, the incorporation of 0.5% steel fibers in the RFA+0.5%SF mix resulted in an absorption of 4.05%, which is slightly lower than that of the RFA mix. The RFA+1%SF mix (with 1% MSF) recorded an absorption of 3.92%, confirming the positive role of steel fibers in bridging microcracks and enhancing dimensional stability, which indirectly restricts moisture ingress (Research & Shaker, n.d.). In addition, the RFA+SL+0.5%SF mix achieved a further reduced absorption of 3.6% The best absorption result was observed in the RFA+SL+1%SF mix, with a value of 3.16%, highlighting the superior effectiveness of combining silica fume with steel fibers in lowering permeability and mitigating the inferior the microstructure of RFA.

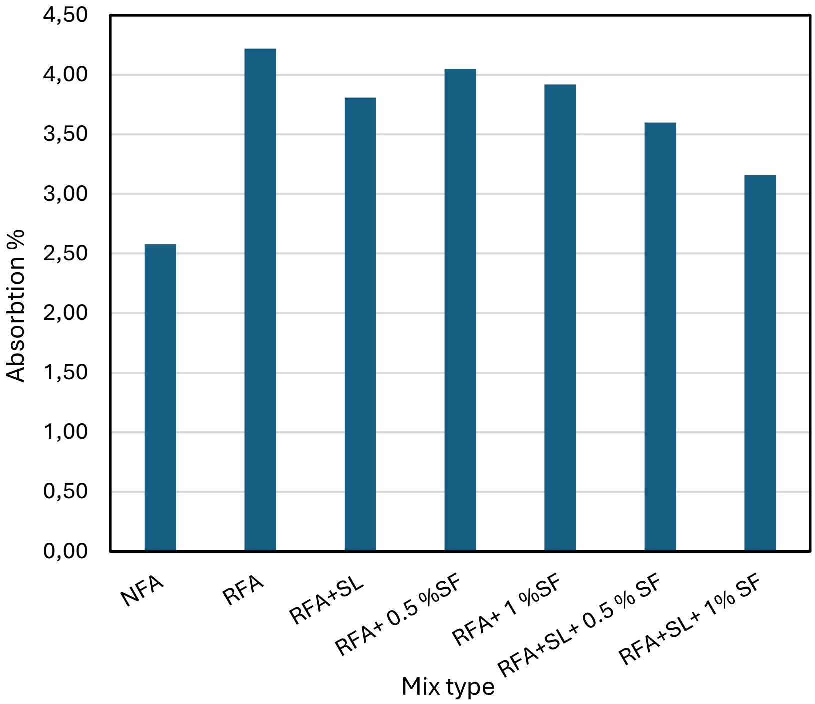

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Figure 7. Result of the absorption test

Dry Density

The dry density results summarized in Table 4 and illustrated in Figure 8 clearly demonstrate how aggregate replacement and the incorporation of supplementary materials influence the density of lightweight concrete (LWC) mixes. The control mix containing natural fine aggregates (NFA) recorded the highest dry density value of 1835 kg/m³. This result is indeed expected, as NFA has relatively higher specific gravity and lower porosity that RFA (Sajedi & Shafigh, 2012). When NFA was fully replaced with 100% RFA, the density dropped to 1726 kg/m³, reflecting a clear decrease compared to the NFA-based mix. This reduction is mainly attributed to the higher porosity and adhered residual mortar on the RFA, which leads to a more porous (Motwani et al., 2013).

In the RFA+SL mix incorporating 15% silica fume, the dry density remained almost comparable at 1721 kg/m³. Here, the density of a concrete mix containing only cement is generally higher than that of a mix in which a portion of the cement is replaced by silica fume. This difference arises because silica fumes have a lower specific gravity (about 2.25) compared to ordinary Portland cement (about 3.15). Conversely, the addition of steel fibers at 0.5% and 1% (RFA+0.5%SF and RFA+1%SF) significantly increased the dry density to 1760 kg/m³ and 1790 kg/m³, respectively. This increase can be directly associated with the high specific gravity of steel fibers, which, besides providing mechanical reinforcement and controlling cracks, also contribute to higher packing density and reduce void content in the hardened concrete (Wu et al., 2024b). The RFA+SL+0.5%SF mix recorded 1748 kg/m³, while the RFA+SL+1%SF mix achieved 1775 kg/m³. These results highlight a balance between the void-filling action of silica fume and the weight contribution of steel fibers, indicating their effectiveness on achieving a relatively dense yet lightweight concrete suitable for structural applications.

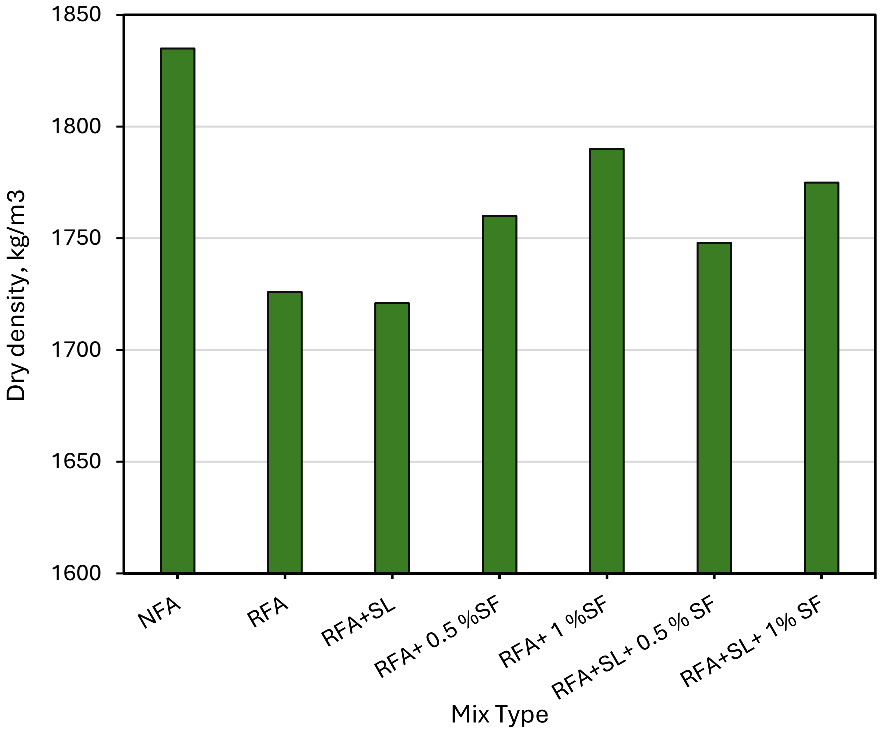

Figure 8. Dry density test

Conclusions

Based on the experimental results of the present study, the following conclusions are drawn:

1. Full replacement of natural sand with recycled fine aggregate reduced compressive and tensile strength by 16% and 14%, respectively, increased water absorption, and slightly decreased dry density.
2. Incorporating 15% silica fume improved compressive strength by 9.2%, splitting tensile strength by 7.4%, reduced water absorption, and maintained acceptable workability.
3. Adding steel fibres enhanced mechanical performance, at 1% fibre content, compressive strength increased by 20.6% and splitting tensile strength by 46.2%.
4. The best performance was achieved with the combined use of silica fume and steel fibres, reaching a HSLWC mix of 58.1 MPa compressive strength and 6.11 MPa tensile strength, with the lowest absorption and adequate fresh properties.
5. All the prepared HSLWC mixes maintained dry density values below 1850 kg/m³, confirming the requirement of structural LWC.
6. The study confirms that combining RFA with silica fume and micro steel fibres produces HSLWC that is suitable for sustainable construction.

Recommendations

1.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.
2.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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