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Behaviour of Fibre-Reinforced Lightweight Self-Compacting Concrete Containing Recycled Brick Aggregate and Silica Fume

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Abstract: Growing of the attention in sustainable construction materials has driven the advancement of lightweight self-compacting concrete (LWSCC), including recycled materials. The present study investigates the fresh and mechanical performance of LWSCC incorporating lightweight expanded clay aggregate (LECA) as coarse aggregate and with complete substitution of natural fine aggregate (NFA) by fine recycled brick aggregate (FRBA). Micro steel fibres (MSF) at 0.5% and 1% volume fractions and silica fume (SF) at 15% cement replacement were introduced. Five different mixes of LWSCC were prepared with the water-to-cement ratio fixed at 0.40. Fresh properties were evaluated using by utilization slump flow, T_{500} time, and L-box tests, while mechanical properties were estimated after 28 days through compressive and splitting tensile strength tests. Dry density and water absorption were also measured in this experimental study. The results presented that full replacement of NFA with FRBA will reduce the strength by an average of 34% compared to the control mix with only NFA. However, incorporation of 0.5% and 1% micro steel fibres (MSF) led to developments in compressive strength of 15.7% and 26.0%, respectively, although the tensile strength improved in 39.1% and 63.4% related to the FRBA reference mix. Similarity, the addition of the silica fume (SF) at 15% resulted in enhancements of 9.4% and 7.4% in particular compressive and tensile strength, identifying it's a positive effect on matrix densification and strength recovery in FRBA-based mixtures. All LWSCC mixes remained within acceptable limits of requirements of the structural lightweight concrete, with dry density below 1850 kg/m³. Water absorption increased with adding of FRBA but was significantly reduced with MSF and SF, reaching as low as 5.60%. All mixes satisfied EFNARC (2005) criteria for flowability, though MSF slightly increased viscosity. Combined use of the recycled aggregates, steel fibres, and silica fume was verified to be an effective approach for producing sustainable LWSCC with satisfactory strength and workability for practical applications.

Keywords: Sustainable lightweight concrete, Self-compacting lightweight concrete, Fine recycled brick aggregate, Micro steel fibre, Silica fume.

Introduction

The Lightweight concrete has grown in importance as a structural material that reduces dead load, enabling lighter construction system, and improving its performance in seismic activities. Lightweight concrete is produced with using of light weight aggregates (LWA) such as light expanded clay, pumice, or else volcanic stone, or through the introduction of air-entraining agents like aluminium powder. Lightweight structural concrete is defined as concrete with a compressive strength of as a minimum 17 MPa at 28-day and a density range between 1120 and 1920 kg/m³, according to ACI 213R-03, (2003) specifications. The performance of LWC is closely associated with aggregate properties. As LWA content increases, reductions in compressive and tensile strengths are often observed (Ke et al., 2009; Yang &Huang 1998). Nonetheless, the environmental and structural advantages of LWC have encouraged its wider adoption, especially when combined with sustainable practices such as the use

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of recycled materials. Construction and demolition waste, particularly crushed clay bricks, has shown promise as an alternative aggregate source, contributing to resource conservation and waste reduction.Recycled brick aggregate (RBA), derived from demolished clay masonry units, has been explored as both coarse and fine aggregate in LWC. Hussein et al. (2022) reported compressive strengths up to 41.5 MPa using RBA with 15% silica fume, though reduced workability was observed due to RBA's high water absorption. Zheng et al. (2018) found that complete replacement of natural aggregate (NA) with RBA caused an 11% reduction in strength. Adem et al., (2019) established that the structural viability of LWC made with clay brick aggregates achieves densities between 1935 and 1990 kg/m³. Further, Adem et al. (2019) explored the possibility of utilized of fine brick aggregate (FBA), coarse brick aggregate (CBA), and brick powder (CBP) as partial cement replacements. Results showed compressive strengths exceeding 20 MPa and densities below 1860 kg/m³. However, slump and workability decreased due to the angular, porous texture of brick particles. Pozzolanic reactivity of CBP was found to slightly reduce porosity at later ages. To overcome these drawbacks and improve the matrix microstructure, silica fume (SF) has been widely adopted. As a highly reactive pozzolanic material, SF densifies pore structure, enhances particle packing, and improves interfacial bonding. Akbulut et al. (2024) found that 10% SF increased compressive strength despite lowering workability. Zarnaghi et al. (2018) observed that 5% SF improved density and pore uniformity, and Türkmen and Gavgalı, (2003) achieved optimal strength and durability using 10% SF with 20% blast furnace slag. Parallel to advances in lightweight and sustainable materials with regard to normal vibrated concrete, the development of lightweight, self-compacting concrete using sustainable materials has also become increasingly important. SCC has the ability to flows under it's a one weight, filling and reaches all parts of the formwork and passing around bars reinforcement without need for any external vibration (Daczko., 2012). This led to improvements of casting speed and quality of the concrete while reducing labor and noise. Combining LWC and SCC has resulted in lightweight self-compacting concrete (LWSCC) which it a composition that offers both reduced density and excellent workability. LWSCC is principally useful in complex structural members and precast concrete systems (Heiza et al., 2018).Ting et al. (2019) highlighted how aggregate properties such as density and porosity critically influence the fresh and hardened performance of LWSCC.Many efforts to increase the sustainability of LWSCC have included the use of waste industrial and by-products as supplementary cementitious replacements. Khan et al.(2023) examined the used of the limestone powder, quartz powder, and glass powder as a partial alternative to cement, concluding that 10% glass powder improved compressive strength and flow-ability. These investigations establish the growing potential of sustainable mix designs. Another enhancement strategy (in addition to the utilization of mineral admixtures) involves the addition of micro steel fibres (MSF), which improve tensile strength, ductility, and crack resistance. Iqbal et al., (2015) stated that a 37% rise in splitting tensile strength with steel fibre adding, while Alabdulkarim et al., (2024) found improvements in the ductility and crack control without compromising other properties. Juradin and Grbeša, (2015) also observed improved homogeneity and reduced segregation in LWSCC containing steel fibres and RBA.

Research Significance

Despite innovations in the development of light-weight self-compacting concrete (LWSCC) incorporating recycled aggregates, studies involving the complete replacement of natural fine aggregate (NFA) with fine recycled brick aggregate (FRBA) remain limited and few, especially when steel fibers and silica fume are combined. In particular, only a limited number of studies have studied the combined effect of completely substituting of the NFA with RBA, alongside the complete replacement of limestone powder (LP) with recycled brick powder (RBP) as a filler material in SCC mixes prepared. FRBA presents challenges such as low strength and high porosity, but its drawbacks may be mitigated through the simultaneous use of SF and MSF. While SF enhances matrix density and reactivity, MSF provides mechanical bridging, improving strength and durability. Therefore, this study aims to develop a sustainable form of LWSCC by replacing 100% of natural fine aggregate with FRBA, supplemented with 0.5% and 1% MSF, and 15% silica fume as a cement replacement. In all prepared mixes, LP was completely replaced with RBP. The study evaluates fresh properties by slump flow, T500, L-box, mechanical performance through compressive and tensile strength, in addition to density and water absorption, to determine the feasibility of these combined materials to produce sustainable LWSCC mixes.

Experimental Work

Materials

In this experimental program, Ordinary Portland Cement (OPC), commercially known as Al-Jiser, was used in accordance with the (IQS., Iraqi Specifications No. (5) 1984).LECA was used as the coarse aggregate in all mixtures. It had a specific gravity of 1.2, 12 mm maximum size, and a water absorption capacity of 12%, conforming to (ASTM C330, 2017). The sieve analysis for LECA is listed in Table 1. Two types of fine aggregates were used: natural aggregate (NA) and fine recycled brick aggregate (FRBA), the latter obtained by crushing brick waste. Both aggregates met the requirements outlined in the Iraqi Specification (‘Iraqi Specifications, 1984).

Following the EFNARC, (2005) guidelines for LWSCC production, recycled brick powder (RBP) was used as a filler to enhance mix density and homogeneity. The maximum size and specific gravity of the used RBP were less than 0.125mm and 2.0, respectively. Figure 1. Silica fume (SF) was incorporated as a partial cement replacement (by 15%) as shown in Figure 2. SF used in this study was an un-densified powder state, with a specific gravity of 2.31. Micro steel fibres (MSF) of 13 and 22 mm (diameter × length) that added (Figure 3). A superplasticizer (SP) is also employed, added by weight of cement. The SP had a light almost brownish colour with a specific weight of 1.070 g/cm³ compliance with ASTM C494-04, (2007) requirements. In this work, tap water was used during the casting and processing.

Table 1. Sieve analysis for LECA

The sieve size (mm)	Cumulative of passing %	ASTM C330 Limits
12.5	100	100
9.5	94.8	80-100
4.75	23.1	5-40
2.36	2.3	0-20

Figure 1. Recycled brick powder

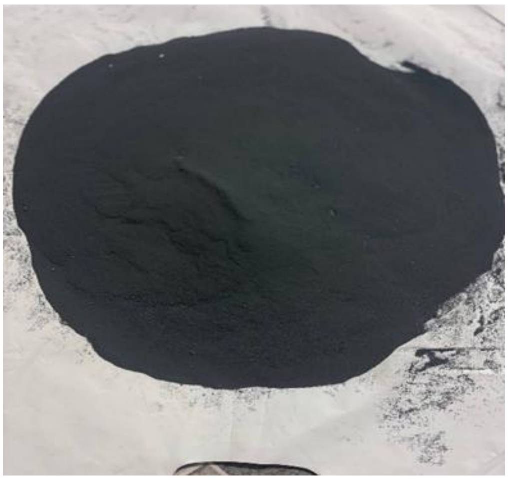

Figure 2. Silica fume (SF) from MegaAdd

Figure 3. Micro steel fibre (MSF)

Mix Proportioning

This experimental program involved the preparation of five LWSCC mixes, as summarized in Table 2. LECA was used as the coarse aggregate in all mixes. Two of the prepared mixtures were prepared with 0% and 100% FRBA instead of sand. To improve the hardened performance of the 100% FRBA mix, micro steel fibres (MSF) were added at two volume fractions (vf), 0.5% and 1%. The fifth mix was prepared with15% silica fume as a partial cement by weight. All mixes were produced with a fixed w/c content of 0.40 was adopted based on laboratory experiment trials to reach a good compatibility ratio between the properties of fresh self-conciliating concrete and compressive strength of the mixes.

Based on the method proposed by Abo Dhaheer et al., (2016), The percentages of materials approved in this program were extracted. Details of the prepared mixtures are illustrated in Table 3. The fine aggregates (NA and FRBA) and LECA were mixed in a saturated surface-dry (SSD) condition. The LECA was soaked for 48 hours to ensure complete saturation and to prevent it from absorbing mixing water during preparation. The dry ingredients were first blended until a uniform blend was achieved, after which water and high-range water-reducing admixture (HRWR) were added, and mixing continued until a homogeneous mix was obtained. Fresh concrete properties were evaluated according to EFNARC, (2005), including the slump flow test, L-box test, and T500 time (Figure 4). The LWSCC mixes were then cast in pre-oiled moulds in a single layer without vibration. Later 24 hours, the molds are removed and the samples are prepared for processing in water for 24 days.

Table 2. Details of the prepared LWSCC mixes

Mix Designation	Details of the mixes
0%FRBA	0% Fine Recycle Brick Aggregate
100%FRBA	100% Fine Recycled Brick Aggregate
100%FRBA+0.5%MSF	100% Fine Recycle Brick Aggregate+0.5% Micro Steel Fiber
100%FRBA+1% MSF	100% Fine Recycle Brick Aggregate+1% Micro Steel Fiber
100% FRBA+15% SF	100% Fine Recycle Brick Aggregate+15% Silica Fume

Table 3. Mixing ratios for LWSCC prepared mixes (Kg/m3)

Mixture Designation	Cement	Water	SP	NFA	FRBA	RBP	LECA	MSF	SF
0%FRBA	438	175	5.3	758	0	108	400	0	0
100%FRBA	438	175	4.25	0	540	108	400	0	0
100%FRBA+0.5%MSF	438	175	5.61	0	535	108	397	39	0
100%FRBA+1% MSF	438	175	6.03	0	530	108	394	78	0
100% FRBA+15% SF	373	175	4.66	0	540	108	400	0	48

*FRBA, MSF, SF, HRWR, NFA, RBP, and LECA denote, respectively, fine recycled brick aggregate, micro steel fiber, silica fume, superplasticizer, natural fine aggregate, recycled brick powder, and lightweight expanded clay aggregate.

Figure 4. Fresh tests of LWSCC: spread slump flow and L-box tests

Hardening Tests

Based on (BS EN 12390-3, 2009), the compressive strength of the LWSCC prepared mixtures were assessed. For each mixture, three sample cube were cast with dimensions 100×100×100 mm, and the average value of the three specimens was recorded. The splitting tensile strength was determined following(BS EN 12390-6, 2009). Three cylindrical specimens, with a diameter of 100 mm and a height of 200 mm, were prepared for each mix. The average of three specimens was used for splitting tensile strength. For the dry density test, three cube specimens with dimensions of 150×150×150 mm were prepared for each mix, following the procedure presented in (ASTM C642-13, 2013). The samples were oven-dried at 110 °C for 24 hours, after which their dry weights were recorded.

After that, cube specimens were immersed in the water for 24 hours to determine their saturated weight to calculate the water absorption capacity. Figure 5 represents the test specimens used in this work.

Figure 5. Specimens preparation for hardened tests

Results and Discussion

During this test, the ability of self-compacting concrete to flow and consolidate in an unconstrained state can be assessed. Visual inspection is also used to assess the mix consistency and homogeneity to detect any signs of segregation occurring. Based on the spread slump flow diameter results, all of prepared mixes classified within the second class according to EFNARC (2005), as the flow spread of the mixes ranged from 680 to 705 mm. This indicates that achieving an acceptable flowability for most structural applications. The results are illustrated in Table 4. The dosage of superplasticizer (SP) varied among mixtures (4.25-6.0 kg/m³), depending on their composition. The mixes of MSF demanded a higher dosage of SP, which is attributed to the increased friction caused by the added fibres, thus reducing the flowability and necessitating additional SP to attain proper fluidity. In this work, the L-box examination was utilization to assess the proparty of passing ability for the concrete through reinforcement obstacles. All mixes achieved L-box ratios ranging of 0.80 to 0.85, which fall within the acceptable limits reported in EFNARC, indicating adequate passing ability even in congested reinforcement zones. In addition, T_{500} time values (the recorded time to reach a flow rate of 500 mm) ranged between 2.4 and 4.5 seconds, confirming the expected viscosity increase of SCC made of 100RFA as well as mixes with MSF. The results demonstrate that all mixes met the fresh state requirements for SCC, with a further increase in T_{500} associated with the inclusion of MSF and the type of fine aggregate used

Table 4. LWSCC fresh properties

Mixes type	Slump flow		L-box ratio	Limit of EFNARC (2005)		
	Spread, mm	T_{500}, s		Spread, mm	T_{500}s	L-box
0%FRBA	685	2.4	0.85	660-750	≥2	≥0.8
100%FRBA (Control)	690	3.2	0.82	660-750	≥2	≥0.8
100%FRBA+0.5%MSF	690	4	0.81	660-750	≥2	≥0.8
100%FRBA+1%MSF	680	4.5	0.80	660-750	≥2	≥0.8
100% FRBA+15%SF	705	3.4	0.83	660-750	≥2	≥0.8

Compressive Strength

Table 5 and Figure 6, establish the compressive strength finding of the various LWSCC mixtures tested at 28 days. The mixture containing 0% FRBA (with only NFA) reached the highest compressive strength, recording 35.5 MPa. In contrast, the control mix with 100% FRBA recorded the lowest strength at 23.5 MPa, reflecting a 33.8% reduction. This decline can be explained by the highly porous nature of FRBA as well as the weak interconnection within the matrix (Zhang et al., 2020). The incorporation of micro steel fibers (MSF) was studied at two volume fraction, 0.5% and 1%, in order to compensate for the reduction. The addition of 0.5% MSF improved the compressive strength to reach 27.2 MPa, which corresponds to an increase of 15.3% compared to the control mix. Further enhancement was achieved at 1% MSF, where compressive strength reached 29.6 MPa, marking a 26.0% improvement. These improvements are no doubt attributed to the crack-bridging action of the steel fibres, which enhances stress transfer, limits crack propagation, and increases the overall toughness of the matrix (Zhang, S., He & & Niu, 2020). Additionally, the effect of incorporating 15% silica fume (SF) as a partial cement replacement was also investigated. The mix of FRBA incorporating with silica fume (SF) reached a compressive strength of about 25.7 MPa, a representative 9.4% increase over the reference mix (100FRBA). This enhancement is explained by the pozzolanic reactivity of silica fume, resulting in a denser microstructure and improved bonding at the aggregate paste interface, as noted in a study presented by (Zhao et al., 2024).

Table 5. Mechanical test results of the LWSCC mixes

Mix designation	*F*cu, MPa	% *Fcu* Relative to control	*Fst*, MPa	*Fst*, % Relative to control	Dry density, kg/m3	Absorption %
0%FRBA	35.5	+33.8	3.71	+34.5	1742	4.46
100%FRBA (Control)	23.5	0.0	2.43	0.0	1537	7.65
100%FRBA+0.5%MSF	27.2	+15.3	3.38	+39.1	1571	6.32
100%FRBA+1%MSF	29.6	+26.0	3.97	+63.4	1608	5.97
100% FRBA+15%SF	25.7	+9.4	2.61	+7.4	1533	5.60

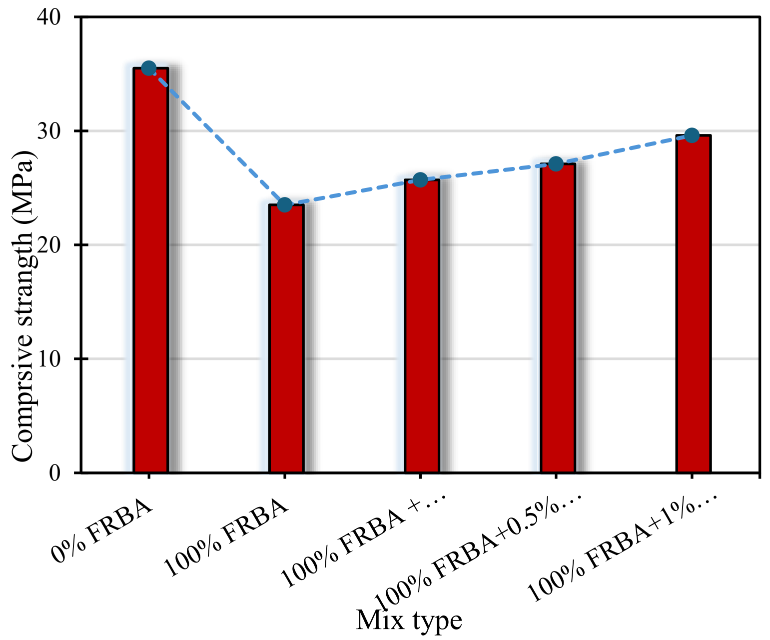

Figure 6. Compressive strength of prepared LWSCC mixes at 28

Splitting Tensile Strength

The data of the splitting tensile strength test after 28 days is provided in Table 5 and shown in Figure 7. The trends observed are somewhat in line with the trends reported on compressive strength specifically on the effect of FRBA and the mitigating effects that silica fume has. The highest splitting tensile strength (Fst) of 3.71 Mpa was attained in the reference mix that consisted of NFA only (0% FRBA). On the contrary, complete replacement of natural fine aggregate by 100 percent FRBA resulted in a large decrease with Fst falling to 2.43 Mpa, a decrease of about 34.5 percent. This degradation is mainly caused by the poor ITZ developed between the cement paste and porous surface of RBA particles (Kinda et al., 2010). In order to overcome this shortcoming MSF were proposed. This was an addition of 0.5% MSF which increased the Fst to 3.38 MPa which was a 39.1% improvement over the reference mix. The increase was further made with 1 percent MSF which gave Fst of 3.97 Mpa, and this was improved by 63.4 percent related to the reference mix. The crack-bridging and energy-dissipating properties of the steel fibres are the cause of these improvements, which, in its turn, lead to improved ductility and tensile resistance (Xu et al., 2006). Based on the test outcomes of this research, it is possible to note that the use of 15% silica fume as a partial replacement of cement in 100% FRBA mix also increased Fst, with the value of 2.61 MPa, or with the increase of 7.4% compared to the control mix. This can be explained by the fact that the pozzolanic reaction of silica fume improves the densification matrix and enhanced bonding between the aggregate paste interfaces.

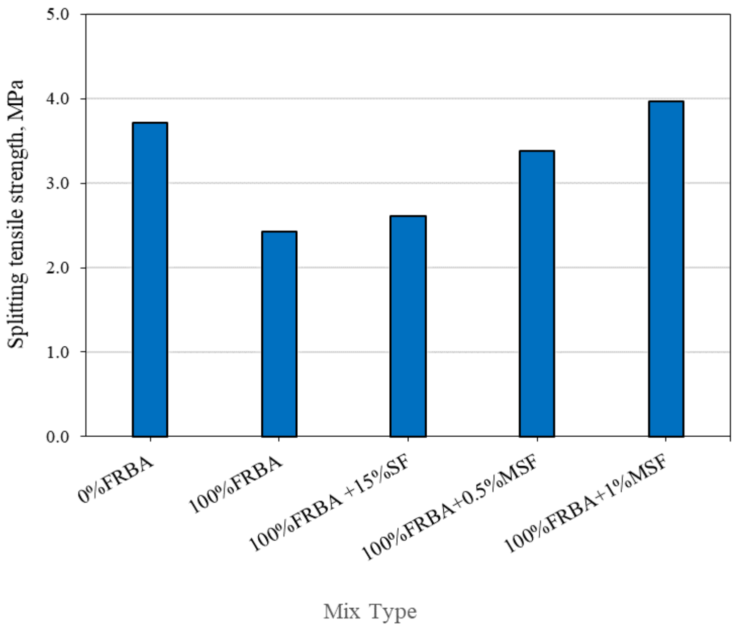

Figure 7. Splitting tensile strength of LWSCC

Dry Density

The dry density results of the LWSCC mixes are shown in Figure 8, and summarized in Table 5. The highest density was observed in the mix casted using 0% FRBA and significantly lower density was obtained when the entire NFA was substituted with 100% FRBA to 1742 kg/m 3 and 1537 kg/m 3 respectively. This decreases it by about 12 per cent, and this is principally due to the lower specific gravity of FRBA and its porous particles. Incorporation of MSF influenced on density. The increment of 0.5% of MSF led to a slight increment to a 1571 kg/m 3 whereas the addition of 1% MSF increased the density to 1608 kg/m 3. This increase is due to the relatively high density of MSF and their ability to reduce internal voids through improved particle interlock and packing efficiency. Additionally, the density of mix 100% FRBA+15%SF (with 15% silica fume) exhibited 1608 kg/m³. It is worth mentioning that the test results confirm that the inclusion of RFA, when combined with steel fibres or silica fume, can yield sustainable structural LWSCC suitable for practical applications with satisfactory density (below 1880 kg/m³, as specified in the standard specification).

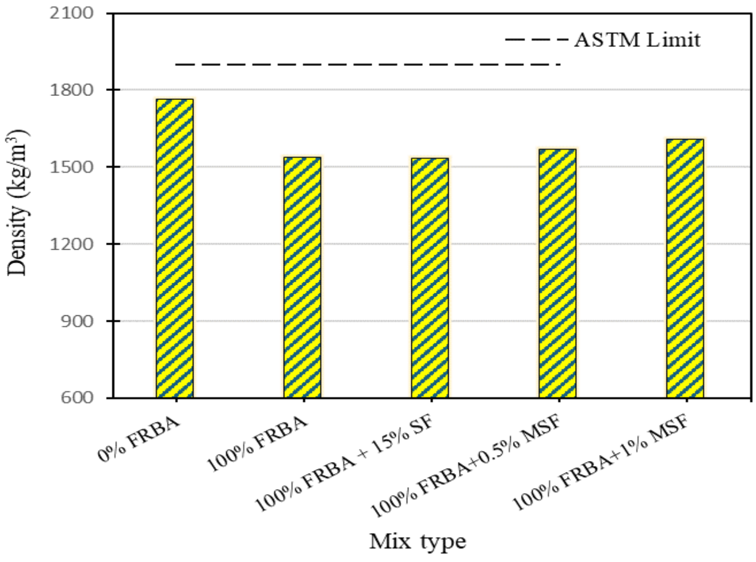

Figure 8. Results of dry density at 28 days for LWSCC mixes

Water Absorption

The water absorption results at 28 days of curing are represented in Table 5 and Figure 9. The mix incorporating natural fine aggregate (0% FRBA) recorded the lowest water absorption value with 4.46%, reflecting its relatively low porosity among the tested mixes. In contrast, the FRBA-based mix exhibited the highest absorption, reaching 7.65%, owing to the porous and absorptive nature of clay brick particles. This indicates that the full replacement of natural fine aggregate with FRBA increases the permeability of the concrete matrix (Khaloo, 1995). Including 0.5% and 1% micro steel fibres (MSF) into LWSCC made with 100% FRBA resulted in a reduction in absorption, with values of 6.32% and 5.97%, respectively.

Additionally, the mix containing 15% silica fume showed an absorption value of 5.60%, which was lower than that of the control FRBA mix. This decline can be attributed to behavior filler effect and pozzolanic activity of silica fume, which contribute to matrix densification and modification of the pore structure (Chaudhary & Sinha, 2020).Generally, it can be established that while the use of FRBA will led to increases of water absorption, the incorporation of steel fibres and silica fume effectively decreases the permeability of the structure, which may in turn enhance the durability of sustainable LWSCC.

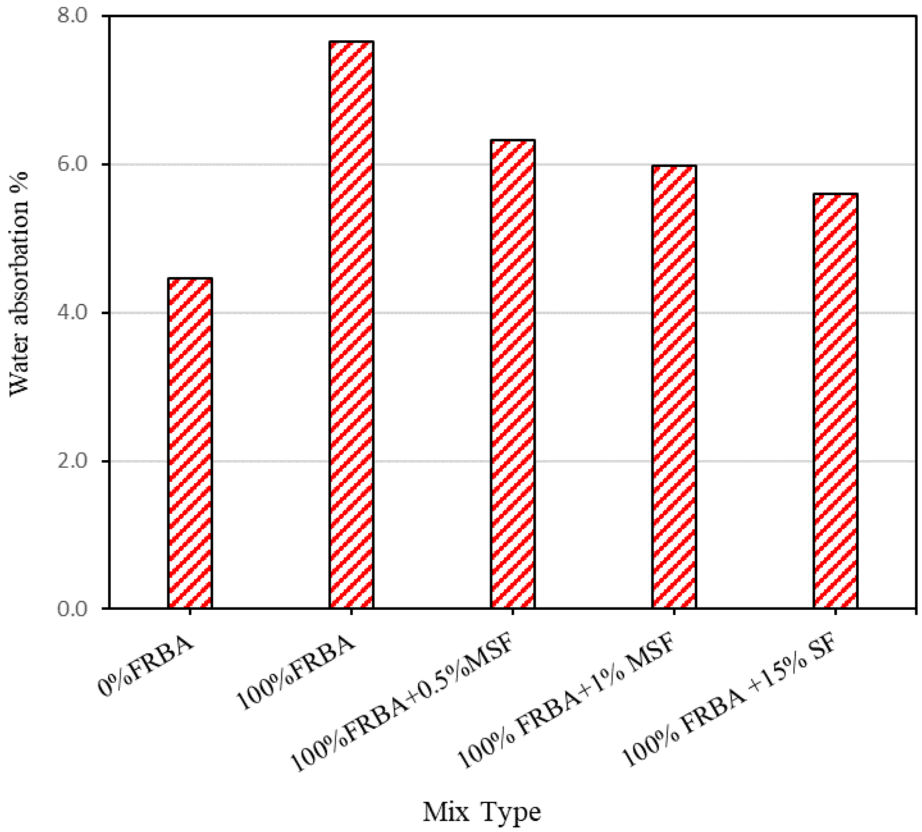

Figure 9. Water absorption finding of LWSCC mixes at 28 days

Conclusion

Based to the results of this research , the following key conclusions recorded:

1. All mixtures of LWSCC made had acceptable fresh properties according to EFNARC (2005) with spread slump flow dimeter values of 680 to 705 mm, L-box passing ability ratios of 0.80 to 0.85 and T 500 times within the target range. Nevertheless, superplasticizer dosages had to be raised to enhance the flowability of the mixture, which was augmented by the presence of micro steel fibres (MSF) that augmented the viscosity of the mixture.
2. The substitution of NFA with 100% FRBA had a larg impact on compressive and splitting tensile strength which was lowered by 33.8% and 34.5 respectively. Although this has reduced the strength, the strength obtained remains under acceptable structural LWC range.

3. Mechanical performance was enhanced successfully with the addition of MSF at 0.5% and 1%. The compressive strength and splitting tensile strength had a 15.7% and 26% and 39.1% and 63.4% increase, respectively, over that of the control mix (100%FRBA).
4. Incorporating of 15% silica fume as a cement replacement material will led to increased of compressive strength in 9.4% and splitting tensile strength by 7.4%.
5. Any mixtures, including those with steel fibre, had dry density value less than 1850 kg/m 3, which was in accordance with the standard, and showed sufficient mechanical performance.
6. With the addition of FRBA, water absorption (to 7.65% maximum) rose but with the addition of MSF and silica fume, it reduced 5.97% and 5.60%, respectively.
7. Although the FRBA use causes porosity and loss of mechanical performance, the disadvantages become manageable through the use of steel fibre and silica fume. Their synergistic combination yields a sustainable LWSCC with sufficient fresh and mechanical characteristics, and is therefore applicable in real life.

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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