

Mechanical and Impact Performance of Lightweight Self-Compacting Concrete Incorporating Two types of lightweight Aggregate, Crumb Rubber, and Steel Fibers

Mustafa S. HAMDI^{1,*}, Ali H. NAHHAB², Mohammed J. KADHIM²

¹ Ph.D. student and Asst. Lecture in Babylon Education Directorate, Ministry of Education, Babylon, Iraq.

² Prof. Dr., College of Engineering, Department of Civil Engineering, University of Babylon, Babylon, Iraq.

* corresponding author: mustafa.hakiem.engh415@student.uobabylon.edu.iq

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Abstract

This study examined the effects of the amount and particles size of Crumb Rubber (CMR), surface treatment with NaOH, and inclusion of micro hook-end steel fiber (MSF) on the performance of lightweight self-compacting concrete (LWSCC). Two types of lightweight aggregates (Lightweight Expanded Clay Aggregate (LECA) and Artificial Attapulgit Aggregate (ATG)) were used as coarse aggregates, with CMR (two particle sizes: 1-3 mm and 3-5 mm) replacing natural sand at a volume percentage of 10-30%. A portion of the rubber was surface treated with NaOH, and 0.5% MSF was added to some mixtures.

The findings revealed that the ATG-based mixtures exhibited acceptable mechanical properties, with approximately 11% and 21% higher compressive strength and modulus of elasticity than the LECA-based mixtures, respectively for structural lightweight concrete application. The strength decreased by 35% with an increase in the CMR content, whereas the impact ductility improved notably (up to 83%). Finer rubber particles exhibited better performance. While NaOH treatment partly recovered strength and improved ductility, the addition of MSF boosted the impact resistance and improved the tensile and flexural strengths by up to 29%. All mixtures met the EFNARC standard requirements for fresh properties, proving that ATG-based LWSCC with CMR and steel fibers provides a more impact-resistant, structurally sound, and sustainable solution for structural applications.

Keywords

Lightweight self-compacting concrete; Artificial Attapulgit Aggregate; LECA; Crumb rubber; Impact strength; Micro hook-end steel fiber (MSF).

1. Introduction

Concrete remains the most popular building material in contemporary infrastructure, its high self-weight and natural aggregate consumption continue to spur the development of lighter and more environmentally friendly substitutes (Adhikary et al., 2022; Gerritse, 1981). Lightweight concrete (LWC) has several advantages in structural applications, such as reduced dead load, improved seismic resistance, better thermal insulation, and the ability to reduce the size of structural elements and foundations (Yang et al., 2022). The American Concrete Institute (ACI) defines structural lightweight aggregate

concrete (SLWC) for structural applications as having an air-dry density of 1440-1850 kg/m³ and a minimum 28-day compressive strength of 17 MPa (*Guide for structural lightweight-aggregate concrete*, 2014).

Self-compacting concrete (SCC) enhances the construction process by self-flowing, filling complex formworks, and penetrating dense reinforcement without vibration, thereby improving the quality and productivity of concrete (Bogas et al., 2012). When SCC is mixed with lightweight concrete (LWC), lightweight self-compacting concrete (LWSCC) with a lower density, satisfactory workability, and durability is produced, making it a suitable material for modern structural applications (Nepomuceno et al., 2018; Sadrmomtazi & Pourahmadi Sefat Arabani, 2025).

The performance of LWSCC is highly dependent on the physical characteristics of lightweight coarse aggregates (LWCA), such as density, porosity, water absorption, shape, and texture, which affect flowability, segregation resistance, and strength (Bogas et al., 2012; Nepomuceno et al., 2018). Various aggregates have distinct fresh and hardened concrete properties. Concrete with Lightweight Expanded Clay Aggregate (LECA) and scoria exhibited different fresh and hardened-state responses, while increasing the LWCA content in the mix tended to decrease compressive strength but maintain workability (Sadrmomtazi & Pourahmadi Sefat Arabani, 2025). Studies on pumice-based LWSCC have shown that a high LWCA content negatively affects the mechanical properties despite providing good flowability (Karadağ et al., 2024), highlighting that the aggregate type is a major design factor, especially when local materials are involved (Bogas et al., 2012; Domagała & Podolska, 2022; Sadrmomtazi & Pourahmadi Sefat Arabani, 2025). The Iraqi clay Attapulgitite, which is available in the central and western regions of Iraq, has previously been found to have a high potential for use as an artificial lightweight aggregate, with a bulk density of approximately 808 kg/m³, as required for LWC (Frayyeh et al., 2014).

The inclusion of steel fibers has been helpful in offsetting the lower stiffness and strength of lightweight aggregates compared with normal aggregates. Steel fibers can significantly enhance the tensile strength, crack control, and ductility of LWC (Abdul Sada et al., 2021; Yang et al., 2022). Therefore, Attapulgitite-based lightweight self-compacting concrete (LWSCC) with fiber reinforcement can be used as an alternative to traditional aggregates such as LECA (Abdul Sada et al., 2021; Hosen et al., 2022).

Crumb rubber (CMR) from waste tires has also been widely investigated for its ability to improve the ductility, energy dissipation, and impact resistance of concrete (Ghoniem & Aboul Nour, 2024; Makki, 2025). However, rubber typically weakens the compressive strength, tensile strength, and elastic modulus owing to the low stiffness of the rubber particles and weak rubber-cement bond (Makki, 2025; Safaan et al., 2018). The size of the rubber particles and replacement ratio play crucial roles, as a large amount of rubber leads to a significant loss of mechanical properties (Ghoniem & Aboul Nour, 2024; Makki, 2025; Makki & Al-Mutairee, 2022), thus forming a ductility-strength trade-off in lightweight construction.

The NaOH treatment of CMR particles improves bonding and partially recovers their mechanical properties (Makki, 2025; Si et al., 2018). The inclusion of steel fibers also compensates for the loss of strength through crack bridging and enhances the flexural and tensile strengths (Al-Kabi & Awad, 2024; Rakaa & Abbas, 2024). Recent research has confirmed that fibers improve the mechanical properties of LWSCC with negligible workability loss (Alabdulkarim et al., 2024; Ali & Awad, 2024) and that fiber-rubber combinations result in improved toughness and crack resistance (Ghoniem & Aboul Nour, 2024; Makki, 2025).

Although numerous studies have been reported on LWSCC, lightweight aggregates, and rubberized concrete separately, limited research has been conducted on their combined effects. To date, there has been no comprehensive investigation of the aggregate type (Attapulgitite vs. LECA), CMR replacement level and size, NaOH treatment of rubber, and steel fiber strengthening in a single LWSCC system or their combined effect on the mechanical and impact responses. To address this knowledge gap, the present study developed and compared LWSCC with ATG and LECA aggregates, considering the effects of CMR replacement, rubber particle size, NaOH treatment, and MSF on the fresh state, mechanical properties, elastic modulus, and impact resistance of the mixes using locally available materials while satisfying structural requirements.

2. Experimental Work

2.1. Materials

2.1.1. Cement

Type I Ordinary Portland Cement was used as the primary binder, complying with Iraqi Quality Standard (IQSNo.4, 2019) in terms of chemical composition, fineness, soundness, setting time, and compressive strength.

2.1.2. Fly Ash (FA)

Class F fly ash conforming to (ASTMC618, 2022) was used as a supplementary cementitious material at 24% by weight of cement in all mixtures

2.1.3. Natural Sand (NS)

Natural sand from the Al-Ekhaider district was used as a fine aggregate, classified as Zone II per (IQSNo45, 1984), with physical and chemical properties within specified limits.

2.1.4. Lightweight Coarse Aggregates (LWCA)

Two types of LWCA were used in this study: locally produced ATG and often using type known LECA (Figure 1). Attapulgate, also known as palygorskite, is a fibrous silicate mineral characterized by a large surface area and acidic surface properties, which render it effective as an adsorbent and catalyst in various applications. It forms under low-temperature surface conditions and is classified as clay (Altun & Aktaş, 2013). Attapulgate clay is found in the regions of Al-Najaf and Karbala, Iraq, as white and bluish-green clay lumps. The raw clay was crushed using a hammer and jaw crusher to a maximum aggregate size of 12 mm, and then fired at 1000 °C for 30 min to produce ATG, following the procedure reported by (Abdul Sada et al., 2021; Hussein et al., 2015). LECA was imported from Iran and used as a conventional LWCA for comparison. Both aggregates were submerged in water for 48 h prior to mixing to reach a saturated surface-dry (SSD) condition (ACI-211.2-98, 2004), and both satisfied the requirements of (ASTMC127-04, 2004; ASTM C330/C330M-17, 2017). The physical properties of the aggregates are listed in Table 1.



Figure 1: Lightweight Coarse Aggregates: a) LECA; b) ATG

Table 1: Physical Properties of Lightweight Coarse Aggregates

Properties	ATG	LECA	Specifications	Allowable Limits
Bulk density [Kg/m ³]	810	400	ASTM C127	≤ 880
specific gravity [OD]	1.42	1.26	ASTM C127	≤ 2.6
Absorption [%]	27	18	ASTM C127	5 - 30

2.1.5. Superplasticizer (SP)

Master Glenium® 54, a high-range water-reducing admixture complying with (ASTMC494, 2024), Types F and G, was used in all mixtures. The SP dosage ranged from 1.0 to 1.5% by weight of binder to achieve the required fresh properties per (EFNARC, 2002) guidelines.

2.1.6. Crumb Rubber (CMR)

The CMR property mention in Table 2 and shown in Figure 2, derived from waste tires, was incorporated as a partial volumetric replacement for natural sand to produce Rubberized Lightweight Self-Compacting Concrete (RLWSCC), enhance sustainability, and improve the behavior of fresh concrete. Replacement levels of 10%, 20%, and 30% by volume were investigated using two particle size fractions: a fine fraction designated S1.18 with particle sizes ranging from 1-3 mm, and a coarser fraction designated S2.36 with particle sizes ranging from 3-5 mm.

Table 2: Chemical and Physical Properties of Crumb Rubber

Chemical Composition		Physical Properties	
Major Rubber Components	Result	Properties	Result
Acetone Extract [-]	10	Fines Modulus	2.25 [-]
Rubber Hydrocarbon [-]	25	Specific Gravity	1.8 [-]
Carbon Black Content [-]	30	Water Absorption	0.61 [%]
Natural Rubber Content [-]	31	Bulk Density	0.45 [g/cm ³]
Ash Content [-]	4		

2.1.7. Micro Hook-End Steel Fibers (MSF)

MSF measuring 13 mm in length, 0.2 mm in diameter, and possessing an aspect ratio (l_f/d_f) of 65, were integrated at a volume fraction of 0.5% in designated mixes (Groups 15-20). Figure 3 shows the MSF samples used in this study and their dimensions.

**Figure 2:** Crumb Rubber (CMR)**Figure 3:** Micro Steel Fiber

2.1.8. NaOH Surface Treatment

A sodium hydroxide (NaOH) solution with 5% concentration was used to treat the CMR particles before incorporating them into concrete mixtures. The rubber particles were immersed in the NaOH solution for one hour to improve the interfacial bonding between the rubber surface and the cement paste matrix, partially recovering the mechanical properties reduced by the rubber inclusion effect then washed by water before using.

2.1.9. Mixing Water

Potable water was used in all mixtures. The water-to-binder ratio (W/Cm) was 0.32 for the ATG-based mixtures and 0.30 for the LECA-based ones.

2.2. Mix Proportion

A total of twenty-two LWSCC mixtures were prepared to investigate the combined effects of LWCA, CMR content, rubber particle size, surface treatment, and MSF on the fresh and hardened properties of the developed mixtures.

CMR was used as a partial replacement of fine aggregates by volume, whereas the water-to-binder ratio (W/b) was maintained at 0.32 for the ATG-based mixtures and 0.30 for the LECA-based ones. The cement content was maintained constant at 380 kg/m^3 , with a consistent binder content of 500 kg/m^3 for all the mixtures. SP was used to achieve the required workability, with a dosage ranging from 1.0% to 1.5% by weight of binder, as listed in Table 3

Table 3: Mix proportions by mass (kg/m^3)

GR	No.	Mix	C	FA	S	LWA	SP [%]	Rub. [%]	CMR	MSF
1	1	ATG-C	380	120	747	432	1.33	-	-	-
	2	LECA-C	380	120	650	450	1	-	-	-
2	3	ATG-R10%-S2.36	380	120	672	432	1.34	10	31	-
	4	ATG-R20%-S2.36	380	120	598	432	1.37	20	62	-
	5	ATG-R30%-S2.36	380	120	523	432	1.44	30	93	-
	6	ATG-R10%-S1.18	380	120	672	432	1.37	10	31	-
	7	ATG-R20%-S1.18	380	120	598	432	1.4	20	62	-
	8	ATG-R30%-S1.18	380	120	523	432	1.45	30	93	-
	9	LECA-R10%-S2.36	380	120	585	450	1.27	10	27	-
	10	LECA-R20%-S2.36	380	120	520	450	1.3	20	54	-
	11	LECA-R30%-S2.36	380	120	455	450	1.37	30	81	-
	12	LECA-R10%-S1.18	380	120	585	450	1.35	10	27	-
	13	LECA-R20%-S1.18	380	120	520	450	1.37	20	54	-
	14	LECA-R30%-S1.18	380	120	455	450	1.4	30	81	-
3	15	ATG-F	380	120	747	432	1.37	-	-	39
	16	LECA-F	380	120	650	450	1.35	-	-	39
	17	ATGF-R10%-S2.36	380	120	672	432	1.4	10	31	39
	18	ATGF-R10%-S1.18	380	120	672	432	1.42	10	31	39
	19	LECAF-R10%-S2.36	380	120	585	450	1.35	10	27	39
	20	LECAF-R10%-S1.18	380	120	585	450	1.38	10	27	39
4	21	ATG-TR10%-S2.36	380	120	672	432	1.31	10	31	-
	22	LECA-TR10%-S2.36	380	120	585	450	1.25	10	27	-

The experimental program aimed to identify the optimal CMR content and make the RLWSCC suitable for structural applications by reducing its self-weight while maintaining high impact resistance and energy dissipation. The mixtures were categorized as follows:

- Group One - Control LWSCC (Mixtures 1 and 2): Two LWSCC mixtures were prepared using ATG and LECA as LWCA. These were used as a control to compare with and evaluate the effect of the LWCA type on the fresh and hardened properties of LWSCC.
- Group Two - RLWSCC (Mixtures 3-14): Twelve mixtures in which fine aggregates were replaced by CMR at 10%, 20%, and 30% of the NS volume. This level of replacement was chosen based on the available literature, which demonstrates that as the rubber content increases, the mechanical properties decrease owing to weak rubber-cement interfacial bonding and low rubber particle stiffness (Ghoniem & Aboul Nour, 2024; Makki, 2025).
- Group Three - Fiber Reinforced RLWSCC (Mixtures 15-20): Six mixtures incorporating 0.5% by volume of MSF, with and without CMR at the optimum level determined in Group Two. This group was designed to assess the ability of the fibers to recover the strength loss and improve their mechanical performance. MSF enhances tensile and flexural behavior by bridging cracks and increasing post-cracking resistance (Ali & Awad, 2024; Yang et al., 2022)
- Group Four: Treated Rubber Mixtures (Mixtures 21-22): This group included two mixtures with 10% CMR (S2.36) treated with NaOH solution for one hour. The treatment was applied to improve the rubber-cement interfacial bonding and enhance both the fresh and mechanical properties (Makki, 2025).

Procedure of mixing, casting, and curing of the samples

Concrete mixtures were prepared using a drum mixer under controlled laboratory conditions. All materials were mixed following a consistent procedure to ensure uniformity, proper dispersion of the constituents, and to achieve the required self-compacting properties of the mixture. Prior to mixing, all molds, testing equipment, and fresh property apparatus were prepared and made ready for use.

The mixing process was performed as follows (Al-obaidey, 2020):

- Preparation of Lightweight Aggregates: ATG and LECA were pre-soaked in water for 48 hours, then removed and left to dry until reaching a saturated surface dry (SSD) condition before mixing (ACI-211.2-98, 2004; Al-obaidey, 2020; Nahhab & Ketab, 2020).
- Pre-blending of supplementary Cementitious Materials: Cement and fly ash were thoroughly pre-mixed before being introduced into the mixer to ensure uniformity.
- Initial Mixing of Aggregates: Coarse and fine aggregates were added to the mixer along with approximately one-third of the mixing water, and the mixer was rotated for 2 min at low speed to ensure uniform distribution of materials.
- Cementitious Materials and Admixture: The mixer was stopped, and the pre-blended cementitious materials were added, followed by the remaining mixing water and SP. To achieve appropriate hydration and dispersion, the mixer was run for 3 min, rested for 3 min (covered), and mixed again for 2 min.
- CMR incorporation: CMR was evenly distributed in the mixture after wet mixing.
- Steel fibers were added gradually to prevent clustering, followed by 3 min of mixing at a medium speed to achieve a uniform distribution.
- Final mixing conditions: Careful mixing produced a homogeneous, cohesive, and segregation-free mixture of components.

The fresh properties of all concrete mixtures were tested immediately after mixing to ensure compliance with the (EFNARC, 2002) requirements. The passing ability, flowability, and stability were evaluated immediately after the mixing.

After the assessment of the fresh properties, the concrete was cast into the molds without external vibration, depending on its self-compacting ability, to achieve complete compacting and adequate filling of the mold. Figure 4 explain the step of casting where the specimens were kept in mold for 24 hours in the laboratory after casting. The samples were then demolded and cured in water tanks at room temperature for 28-day to reach the desired age for testing.



Figure 4: Casting and Curing Of LWSCC Mix

2.3. Fresh and Hardened Concrete Test

A series of tests was conducted to assess the fresh and hardened properties of the developed concrete mixes according to the appropriate standards.

2.3.1. Fresh Concrete Tests

The fresh properties of LWSCC were tested immediately after mixing, according to (EFNARC, 2002) guidelines. The properties related to the fresh state of the concrete included slump flow and T500 (time required to reach 500 mm) to measure flowability, V-funnel to measure viscosity, L-box to measure passing ability, and V-funnel at 5 min (VFT5) to measure segregation resistance.

2.3.2. Hardened Concrete Tests

The hardened concrete properties were evaluated at 28 days of water tank curing and included compressive strength using $100 \times 100 \times 100$ mm cubes in accordance with (Testing hardened concrete. Part 3, Compressive strength of test specimens, 2019), splitting tensile strength using 100×200 mm cylinders following (ASTMC496/C496M, 2014), flexural strength using $100 \times 100 \times 400$ mm prisms according to (ASTMC78/C78M, 2018), and static modulus of elasticity using 100×200 mm cylinders based on (ASTMC469, 2014). In addition, the impact strength was assessed using the drop-weight test in accordance with (ACI-544.4, 2018), based on the procedure proposed by (Makki, 2025; Makki & Al-Mutairee, 2022), as shown in Figure 5. The test was conducted in 28 days, and the average of three samples was adopted. The impact ductility ratio (IDR) was used to evaluate the post-cracking impact resistance of the concrete. For each test three samples casting and the average of these samples taken.

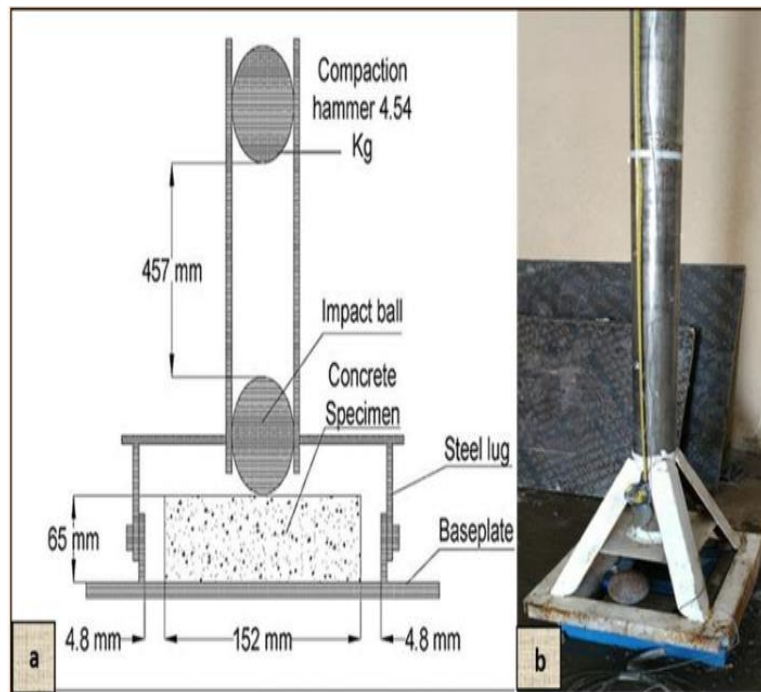


Figure 5: Impact Resistance Machine: a) Cross- Section of the Impact Strength Test Setup; b) Impact Test Device

3. Results And Discussion

3.1. Fresh Properties

Table 4 summarizes the fresh properties of the LWSCC mixtures, which are discussed in the following subsections in accordance with (Bogas et al., 2012; Emiroglu et al., 2008) acceptance criteria.

Table 4: Results of LWSCC Fresh Properties

GR	No.	Mix	Slump flow [mm]	T500mm [sec]	VF [sec]	VFT5 [sec]	L-Box [-]
1	1	ATG-C	733	2.5	8	11.5	0.98
	2	LECA-C	744	3	7	10	1
2	3	ATG-R10%-S2.36	721	3	9	12	0.93
	4	ATG-R20%-S2.36	718	3.7	12	14	0.84
	5	ATG-R30%-S2.36	689	5	13	15.5	0.8
	6	ATG-R10%-S1.18	725	2.7	8.5	11	0.95
	7	ATG-R20%-S1.18	712	4	11	13.5	0.87
	8	ATG-R30%-S1.18	700	5	12.5	15	0.85
	9	LECA-R10%-S2.36	728	3.5	8	10.5	0.94
	10	LECA-R20%-S2.36	719	4	10.7	13	0.91
	11	LECA-R30%-S2.36	707	5	12	14.5	0.86
	12	LECA-R10%-S1.18	737	3.3	7.5	9.7	0.97
	13	LECA-R20%-S1.18	723	4	10	12	0.86
	14	LECA-R30%-S1.18	715	5	11.5	14	0.82
3	15	ATG-F	726	3.7	11	13	0.88
	16	LECA-F	730	4.7	10	12	0.9
	17	ATGF-R10%-S2.36	717	4.5	12	14	0.83
	18	ATGF-R10%-S1.18	721	4	11.7	14.5	0.85
	19	LECAF-R10%-S2.36	715	5.2	12.5	14.6	0.85
	20	LECAF-R10%-S1.18	727	5	11.5	15	0.87
4	21	ATG-TR10%-S2.36	724	2.8	8	10	0.95
	22	LECA-TR10%-S2.36	726	3	7.5	11	1

3.1.1. Slump Flow

The slump flow and T500 data shown in Table 3, Figure 6, and Figure 7 demonstrate that all mixtures satisfy the EFNARC 2002 requirements, with slump flow values ranging from 650 to 800 mm and T500 values between 2 and 5 s, thus proving their sufficient self-compacting capability.

The control mixture slump flow values were 733 mm (ATG-C) and 744 mm (LECA-C), with T500 times of 2.5 s and 3 s, respectively. The higher flowability of the LECA mixtures was attributed to their smoother surface texture and more spherical particle shape, which reduced the internal friction. The ATG mixtures exhibited slightly lower slump flow and shorter flow times owing to their rougher surface texture and higher water absorption capacities.

An increase in the CMR content progressively reduced the slump flow and increased the T500 values, indicating higher viscosity. The ATG mixtures dropped from 733 to 689 mm ($\approx 6\%$) with T500 rising from 2.5 to 5 s, whereas the LECA mixtures decreased from 744 to 707 mm with T500 increasing from 3 to 5 s.

This behavior is governed by the low stiffness, irregular geometry, and hydrophobic nature of the rubber particles, which increase the internal resistance and reduce the cohesion of the concrete. The smaller rubber particles (S1.18) had a slightly larger slump flow and exhibited T500 times shorter than the larger rubber particles (S2.36) at the same replacement ratio owing to improved particle packing and less obstruction in the flow.

The use of steel fibers slightly decreased the slump flow and significantly increased T500 because of fiber interlocking and increased internal friction (Al-Kabi & Awad, 2024). The slump flow and T500 were not significantly influenced by the addition of rubber treated with NaOH, suggesting that it had insignificant effect on the rheology of the mixture. The overall results suggest that although the use of rubber and fiber slightly decreased flowability and increased viscosity, all mixtures retained acceptable self-compacting ability.

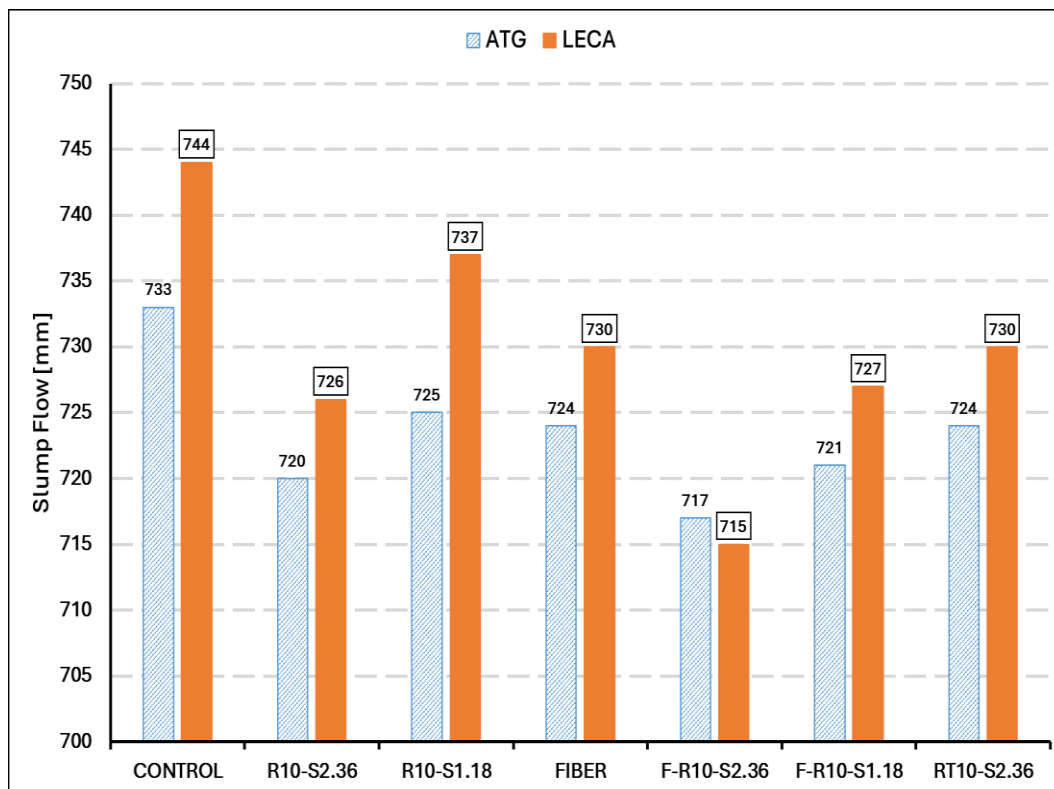


Figure 6: Slump Flow Diameter Result

3.1.2. V-Funnel

ATG-based mixtures consistently demonstrated extended V-funnel (VF) and V-funnel after 5 min (VFT5) values compared to LECA-based mixtures, owing to the angular particle shape, increased porosity, and enhanced water absorption of ATG, which increased the internal friction and apparent viscosity of the fresh mixture. This behavior aligns with the results of (Nahhab & Ketab, 2020), which indicated that angular LWCA with elevated absorption enhanced the viscosity-related fresh property values of LWSCC. All findings met the EFNARC approval standards of 6-12 s for VF and 6-15 s for VFT5 (see Fig. 6).

For all mixes, the VF and VFT5 values increased with an increase in the CMR replacement level from 10% to 30%. VF values increased by 62.5% and 71.4% for the ATG and LECA control mixtures, respectively, at 30% replacement level. The low density, hydrophobic nature, and irregular shape of the rubber decrease the gravitational force and increase the particle resistance. Owing to funnel-shaped clogging, larger rubber particles (S2.36) had higher VF and VFT5 values at the same replacement ratios compared with smaller particles (S1.18). This effect has been reported for the RLWSCC (Lv et al., 2019).

The inclusion of 0.5% MSF increased the VF and VFT5 owing to enhanced plastic viscosity and flow resistance. The rubber-fiber interaction increased the aggregation and resistance to flow in fresh concrete when using MSF or CMR. In contrast, the VF and VFT5 values of the NaOH-treated rubber formulations decreased compared to those of the untreated rubber formulations, as the surface treatment of the rubber improved the rubber-paste bonding, prevented particle clustering, and improved flow uniformity. This result is consistent with (Si et al., 2018), which suggested that the alkaline treatment of rubber improved the workability consistency of self-consolidating concrete (SCC).

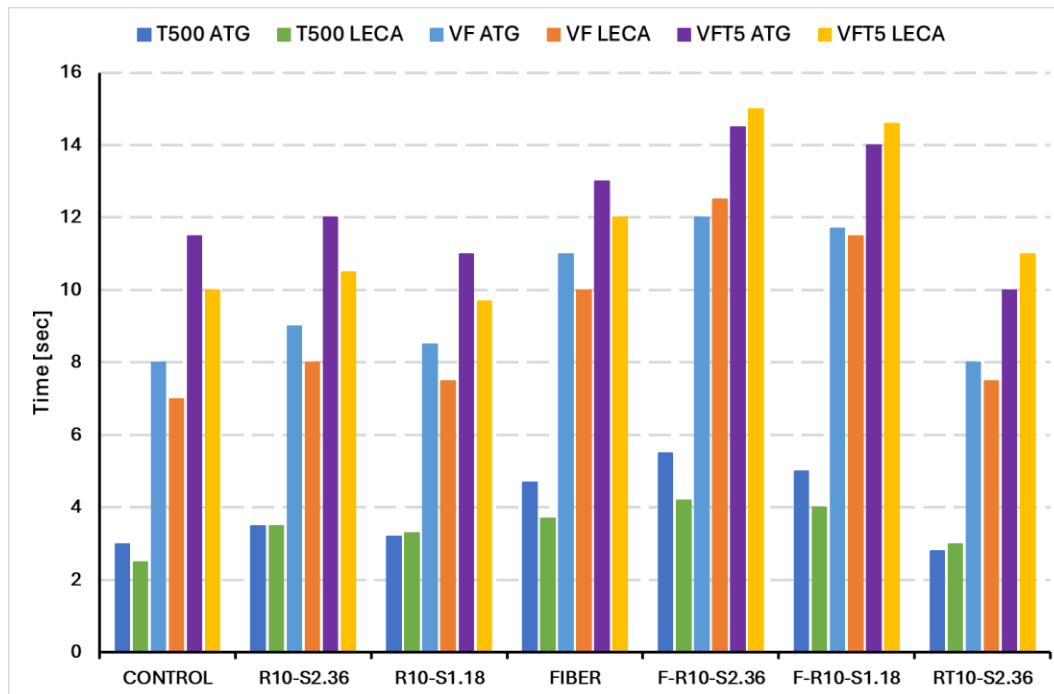


Figure 7: T500, VF, and VFT5 value of LWSCC mixes incorporating ATG and LECA

3.1.3. L-Box

The L-box blocking ratios (h_2/h_1) for all mixtures ranged from 0.80 to 1.00, meeting the EFNARC requirements (Figure 8). LECA-based mixtures achieved higher ratios than ATG-based mixtures because the spherical aggregate shape reduced interparticle friction and allowed for easier passage through reinforcement gaps. Increasing the CMR content from 0% to

30% reduced the L-box ratio by 18% and 14% for the ATG and LECA mixtures, respectively, owing to the irregular particle geometry and the higher frictional resistance. At the same replacement level, coarser particles (S2.36) produced lower blocking ratios than finer particles (S1.18), consistent with the greater flow obstruction from larger particle sizes (Lv et al., 2019). Adding 0.5% MSF further reduced the passing ability through fiber interlocking, with the largest drop recorded when MSF and CMR were combined. The NaOH-treated mixtures partially recovered their passing ability, reaching ratios of 0.95 and 1.00 for ATG and LECA, respectively. This was attributed to better rubber-paste adhesion and a more consistent particle distribution in the fresh mix.

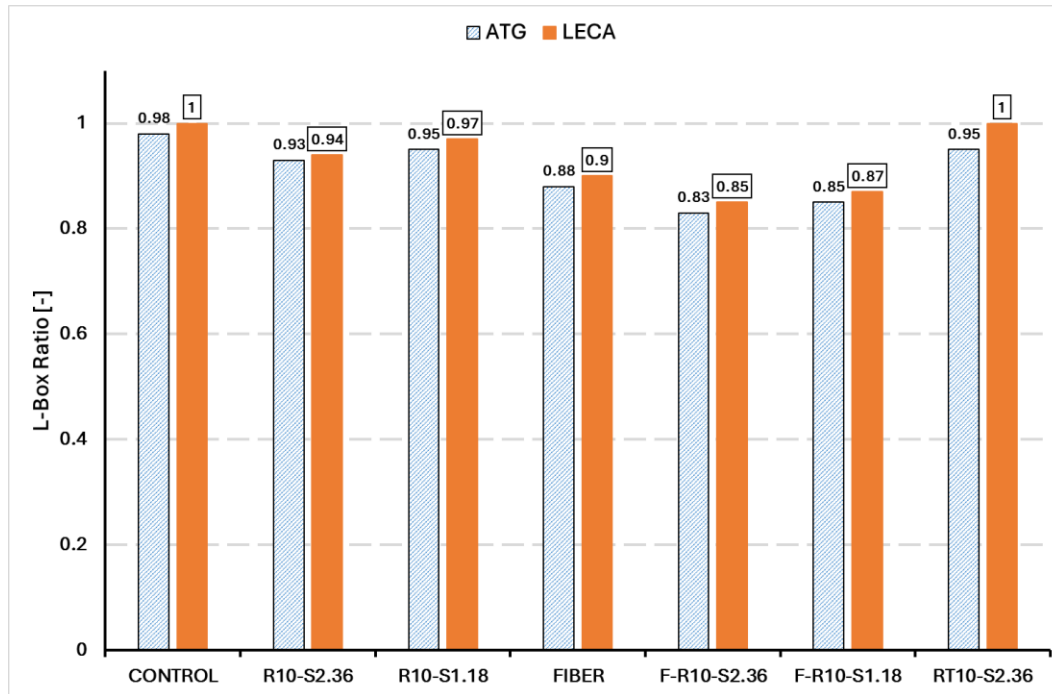


Figure 8: L-Box values of LWSCC mixes incorporating ATG and LECA

3.2. Hardened Concrete Properties

The hardened properties at 28 days are presented in Table 5 and discussed below. Also, Error bars adding to in Figures 9, 10, 11, 12, and 13 to graphically which indicating one standard deviation have been included to show the variability across repeated specimens.

3.2.1. Compressive Strength

All mixtures achieved a compressive strength above the minimum structural requirement of 17 MPa (Figure 9), as recommended by (Akers et al., 2013), after 28 days of curing, demonstrating the structural suitability of all LWSCC systems. The ATG control achieved 35.0 MPa, which was 11% stronger than the LECA control (31.5 MPa) owing to the higher stiffness and angularity of the aggregates, which facilitated interlocking and improved the ITZ between aggregates and cement paste.

The inclusion of CMR decreased the compressive strength of all mixtures. The ATG-based mixtures exhibited a reduction in compressive strength as the rubber content increased from 10% to 30%, decreasing from 28.7 MPa to 23.6 MPa (S2.36) and from 31.2 MPa to 25.4 MPa (S1.18), resulting in a decline of 32.6% and 27.4%, respectively, relative to the control. Losses of 35.2% and 26.0% were observed for the LECA-based S2.36 and S1.18 mixtures, respectively. This reduction is due to the poor rubber-cement ITZ, low CMR elastic modulus, and increased amount of deformable phase, which together encourage early micro-cracking under compression (Irmawaty et al., 2020; Poon et al., 2004).

Table 5: Results of LWSCC Hardened Properties at 28 days

GR	No.	Mix	Comp. [MPa]	Split. [MPa]	Flex. [MPa]	E [GPa]	IDR [-]
1	1	ATG-C	35	3.5	3.36	24.2	1.73
	2	LECA-C	31.5	2.88	2.84	20	1.57
2	3	ATG-R10%-S2.36	28.7	2.97	3.4	21.2	2.61
	4	ATG-R20%-S2.36	26.3	2.59	3.2	17.5	2.7
	5	ATG-R30%-S2.36	23.6	2.44	2.85	16.5	2.5
	6	ATG-R10%-S1.18	31.2	3.3	3.6	23.5	3.16
	7	ATG-R20%-S1.18	29.1	3.31	3.55	18.3	3.3
	8	ATG-R30%-S1.18	25.4	3.05	3.3	17.7	3.2
	9	LECA-R10%-S2.36	26.2	2.8	3.1	18.4	2.44
	10	LECA-R20%-S2.36	23.2	3	2.8	17.8	2
	11	LECA-R30%-S2.36	20.4	2.7	2.65	15.5	2.2
	12	LECA-R10%-S1.18	27.5	2.83	3.25	19.7	3
	13	LECA-R20%-S1.18	25.3	2.75	2.86	16.5	3.2
	14	LECA-R30%-S1.18	23.3	2.5	2.7	13.5	2.7
3	15	ATG-F	34.6	3.91	4.05	25.5	2.62
	16	LECA-F	32.7	3.12	3.67	21	2.35
	17	ATGF-R10%-S2.36	26.4	3.67	4.56	22.3	3.92
	18	ATGF-R10%-S1.18	29.8	3.86	4.73	23	4.22
	19	LECAF-R10%-S2.36	25	2.87	3.7	20.6	3.7
	20	LECAF-R10%-S1.18	28.1	3.53	4.1	21	3.82
4	21	ATG-TR10%-S2.36	29.3	3.52	3.47	22.6	3.4
	22	LECA-TR10%-S2.36	27	2.92	2.82	19	3

Finer particles (S1.18) had greater compressive strength than larger particles (S2.36) at the same replacement levels, as the decreased particle size reduced the stress concentration and increased the cement matrix density. A 10% replacement was found to be optimal, as it limited the loss in strength to 10-18% and produced adequate structural properties (Lv et al., 2019; Prasad, 2024).

The addition of MSF had a minimal effect on compressive strength. The ATG-based mixtures displayed a marginal 1.1% loss due to fiber clumping and air voids, whereas the LECA-based mixtures exhibited approximately 3.8% gain, suggesting that the fibers compensated for the low matrix stiffness of the LECA. The NaOH treatment increased the compressive strength by 5.8% and 3.0% for the ATG- and LECA-based mixtures, respectively, compared to the untreated R10%-S2.36 mixtures, owing to improved rubber-paste bonding and strength of the ITZ (Si et al., 2018).

3.2.2. Splitting Tensile Strength

The splitting tensile strength trends followed the same pattern as that of compressive strength (Figure 10). The ATG-based control mixture exhibited a splitting tensile strength of 3.5 MPa, whereas the LECA-based control mixture exhibited a splitting tensile strength of 2.88 MPa. The incorporation of CMR produced a more pronounced relative reduction in the tensile strength than in the compressive strength, reflecting the higher sensitivity of the tensile performance to the ITZ quality, where the weak rubber-cement interface governs crack initiation and propagation under direct tension (Emiroglu et al., 2008).

For the ATG-based mixtures with S2.36 rubber, the tensile strength decreased from 3.50 MPa at 0% to 2.97, 2.59, and 2.44 MPa at 10%, 20%, and 30% replacement, corresponding to reductions of 15.1%, 26.0%, and 30.3%, respectively. The finer rubber (S1.18) produced much lower reductions of 5.7%, 5.4%, and 12.9% at the same levels, clearly showing that the size of the rubber particles affects the tensile performance, affecting the level of stress concentration within the matrix. For the mixtures with LECA, the tensile strength decreases of the S1.18 fraction were 2.8%, 4.2%, and 6.3%, while those of the S2.36 fraction were 14.3%, 16.4%, and 28.0%, again showing the better performance of the finer rubber fractions for both aggregate types.

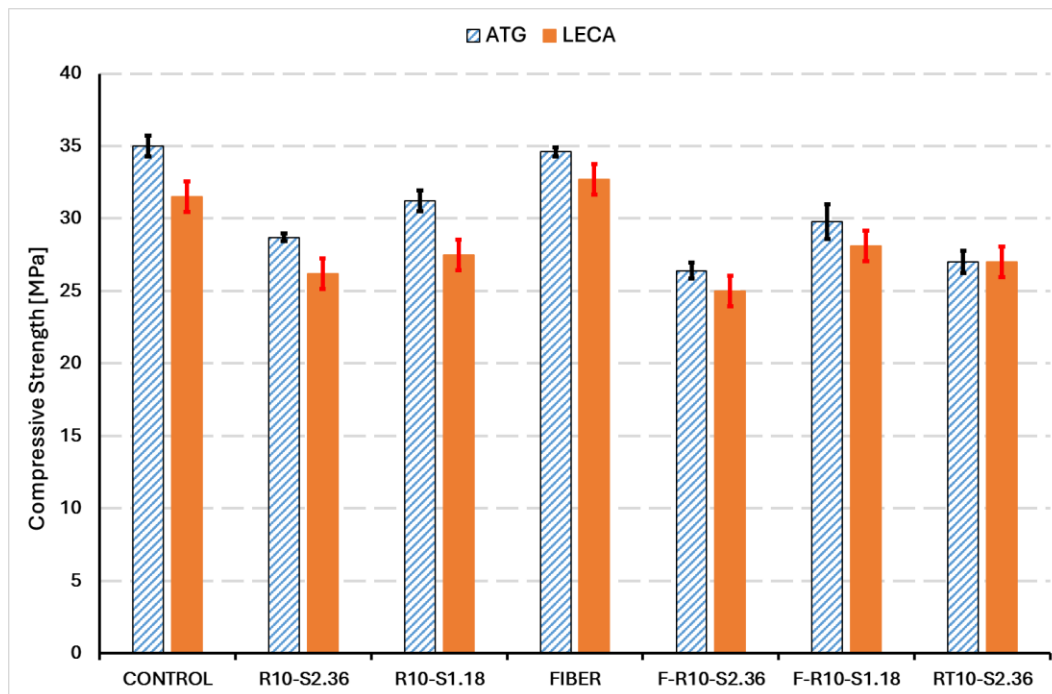


Figure 9: Compressive Strength of LWSCC with CMR and MSF Incorporation Using Different LWCA Type

The addition of 0.5% MSF significantly improved the splitting tensile strength through crack-bridging mechanisms and enhanced stress redistribution across the matrix (Kadhum, 2015; Nis, 2018). For the RLWSCC mixtures of ATG-based with 10% CMR, the tensile strength increased by 23.6% and 12.5% for the S2.36 and S1.18 fractions, respectively, relative to the corresponding fiber-free mixtures. The more pronounced improvement observed in the ATG-S2.36 mixtures reflects the greater capacity of the fibers to compensate for the larger stress concentration zones introduced by the coarser rubber particles. Corresponding improvements of 2.5% and 24.7% were recorded for the LECA-based mixtures. NaOH surface treatment further enhanced the tensile strength, with ATG-TR10%-S2.36 recording an 18.5% increase over the untreated ATG-R10%-S2.36 mixture, while the LECA-based counterpart showed a more modest improvement of 4.3%, confirming the beneficial role of alkaline treatment in strengthening the rubber-paste interfacial bonding, consistent with the findings reported by (Si et al., 2018).

3.2.3. Flexural tensile strength

The 28-day flexural strength results demonstrated that the ATG-based control mixtures achieved a modulus of rupture of 3.36 MPa, exceeding that of the LECA-based mixtures (2.84 MPa) by approximately 18.3% (Figure 11), which is consistent with the compressive and splitting tensile strength trends and is attributable to the superior aggregate-paste interlocking associated with the angular morphology of ATG particles.

The flexural strength was greater than that of the control mixtures for the 10% CMR replacement level for both aggregate types. The ATG-based mixtures had gains of 10.2% and 15.5% for the S1.18 and S2.36 fractions, corresponding to 3.6 and 3.4 MPa, respectively, while the LECA-based mixtures had gains of 18.5% and 20.4%, corresponding to 3.25 and 3.1 MPa, respectively. The crack-bridging and stress redistribution associated with the rubber particles delayed the formation and propagation of cracks. However, the trend was reversed with higher CMR substitution levels. At 30% replacement level, the flexural strength dropped to 3.3 and 2.85 MPa for the ATG-S1.18 and ATG-S2.36 mixtures and 2.7 and 2.65 MPa for the LECA-based mixtures, which corresponds to up to 15% reduction relative to the control values owing to the softer rubber-cement ITZ and greater strain of the composite matrix.

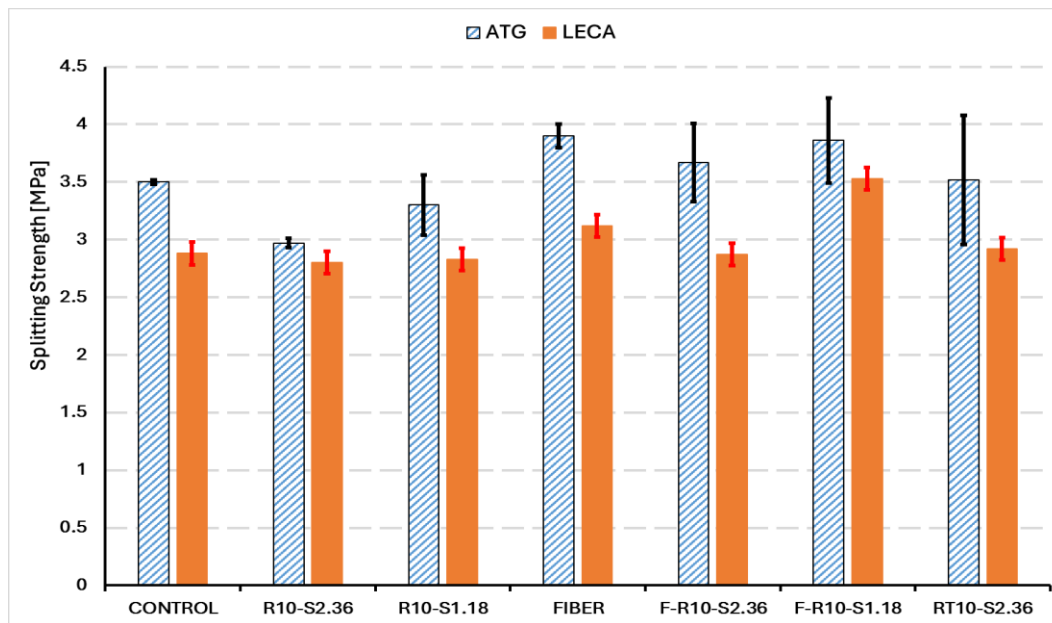


Figure 10: Splitting tensile strength of LWSCC with CMR and MSF Incorporation Using Different LWCA Type

The flexural strength was significantly improved across all mixes with the addition of 0.5%-MSF. The fiber-only ATG and LECA control mixes attained 4.05 and 3.67 MPa, respectively, up 20.5% and 29.2% from unreinforced controls. The flexural strength increased by 12.6% and 16.8% compared to the fiber-only control mixes for hybrid mixtures combining MSF with 10% CMR, reaching 4.73 MPa (ATGF-R10%-S1.18) and 4.10 MPa (LECAF-R10%-S1.18). As stated in (Balendran et al., 2002; Gray & Johnston, 1987), effective crack bridging, fiber pullout resistance, and increased post-cracking ductility under flexural stress are responsible for these improvements. The enhancement in flexural strength exceeded that of the compressive and splitting tensile strengths, aligning with the predominant influence of tensile stress during flexural loading and the advantageous fiber alignment in the tension zone (Balendran et al., 2002; Frank, 1979). NaOH-treated rubber mixes exhibited minor flexural strength recovery compared to untreated rubber mixes owing to the increased rubber-paste bond quality, which encourages ductile failure (Si et al., 2018).

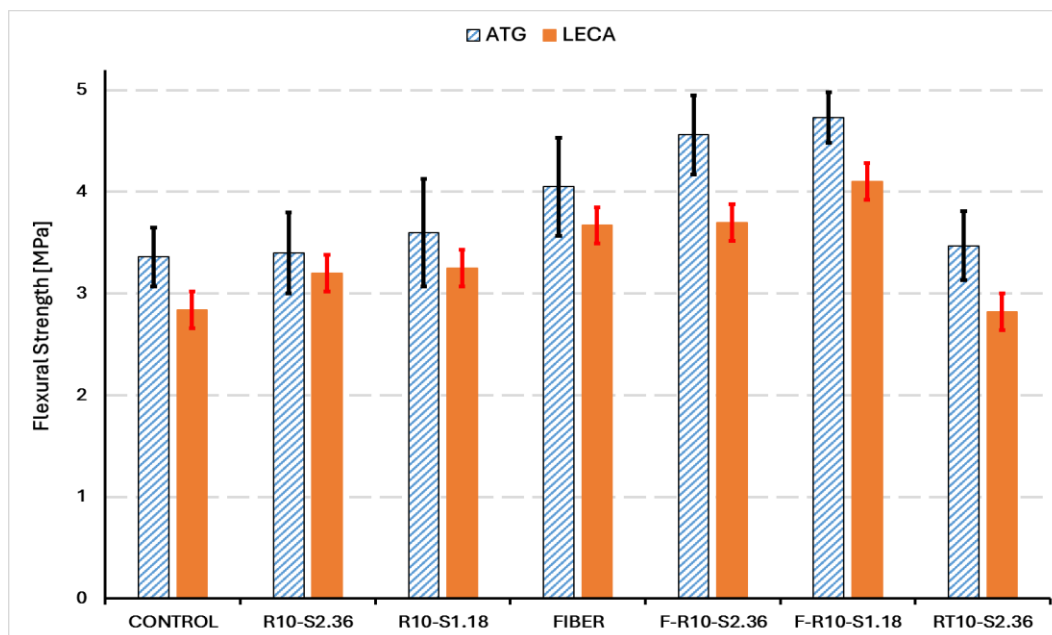


Figure 11: Flexural Strength of LWSCC with CMR and MSF Incorporation Using Different of LWCA Type

3.2.4. Static Modulus of Elasticity

The results for the static modulus of elasticity (E_c) of the concrete showed that the control ATG-based mixture attained 24.2 GPa, a 21% increase over the LECA control 20 GPa (Figure 12). This difference suggests increased particle stiffness and improved interfacial transition zone (ITZ) quality associated with ATG, which contributes to the increased stiffness of the concrete matrix.

An increase in CMR content from 10% to 30% led to a progressive decrease in E_c for both types of aggregates. The E_c for the ATG-based concrete decreased from 21.2 GPa (R10%-S2.36) to 16.5 GPa (R30%-S2.36), a reduction of approximately 22.2% compared to the 10% replacement level, while for the S1.18 mixtures, it decreased from 23.5 to 17.7 GPa, a reduction of approximately 24.7%. The corresponding reductions for the LECA-based mixtures ranged from 18.4 to 15.5 GPa (S2.36) and 19.7 to 13.5 GPa (S1.18), which corresponded to 15.8 and 31.5% reductions, respectively. These decreases are attributed to the low modulus of elasticity of the rubber particles and their deformability, which creates soft inclusions in the cement matrix, thereby reducing the composite modulus, as previously reported by (Chylík et al., 2019; Eldin Neil & Senouci Ahmed, 1993).

The incorporation of 0.5% MSF increased E_c by approximately 5.4% and 5.0% for the ATG and LECA mixtures, respectively, which was attributed to improved crack control and enhanced stress transfer across the matrix, respectively. NaOH-treated rubber mixtures recovered partial stiffness compared with untreated counterparts; ATG-TR10%-S2.36 achieved 22.6 GPa versus 21.2 GPa for untreated ATG-R10%-S2.36 attributed to strengthened rubber-paste adhesion within the ITZ, promoting more effective stress transfer under compressive loading.

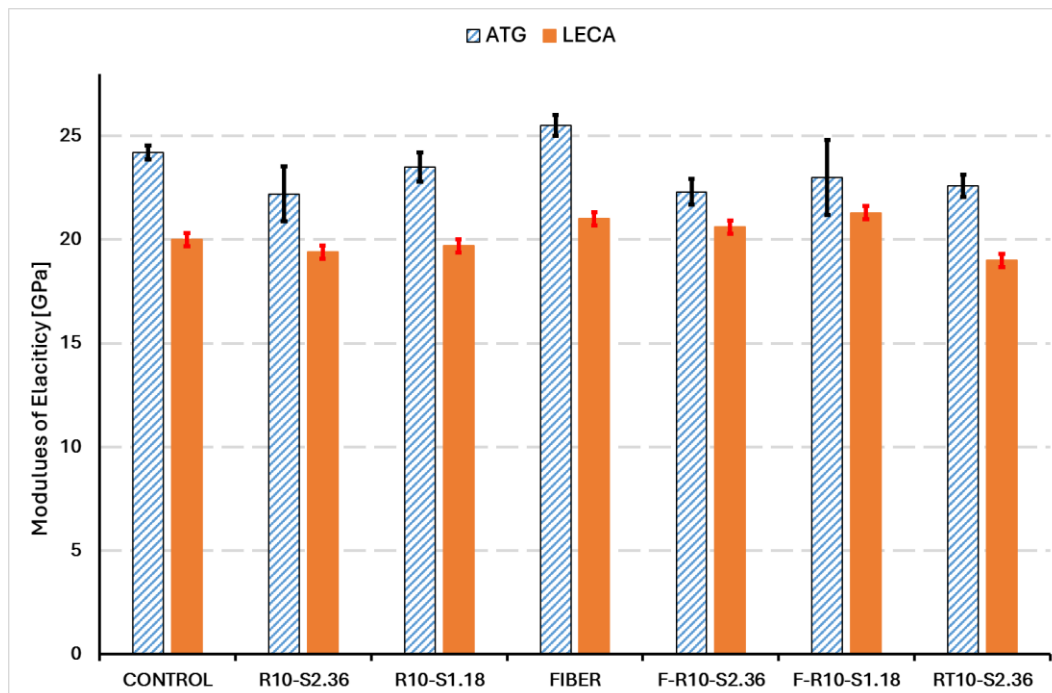


Figure 12: Static Modulus of Elasticity of LWSCC with CMR and MSF Incorporation Using Different LWCA Type

3.2.5. Impact Ductility Ratio

The impact ductility ratio (IDR), which is calculated as the ratio of the number of blows to failure (N_2) to the number of blows to the first visible crack (N_1), was used to assess the impact resistance after cracking (Figure 13). The control mixture with ATG had an IDR of 1.73, which was 10.2% higher than that of the LECA control (1.57) owing to better aggregate

interlock and more progressive crack development owing to the angular shape of ATG. While the static properties were reduced, the IDR was improved with the use of CMR in all mixes.

The IDRs for ATG-S1.18 and ATG-S2.36 at 10% replacement were 3.16 and 2.61, respectively, representing increases of 82.7% and 50.9% over the ATG control. Smaller rubber particles (S1.18) always exhibited higher IDR values than larger particles (S2.36) owing to the more uniform energy dissipation and reduced stress concentration. The trade-off between the static strength and IDR of rubberized concrete has been well documented by (Khalil et al., 2015; Makki & Al-Mutairi, 2022). The addition of 0.5% MSF increased the IDR due to crack-bridging and load carrying; hybrid mixes of MSF with 10% CMR recorded maximum IDR of 4.22 and 3.92 for ATGF-R10%-S1.18 and ATGF-R10%-S2.36, respectively. The IDR of the NaOH-treated mixes (3.40 and 3.00 for ATG and LECA, respectively) improved owing to the enhanced rubber-paste interfacial transition zone, which allowed a stable post-cracking behavior under impact loads.

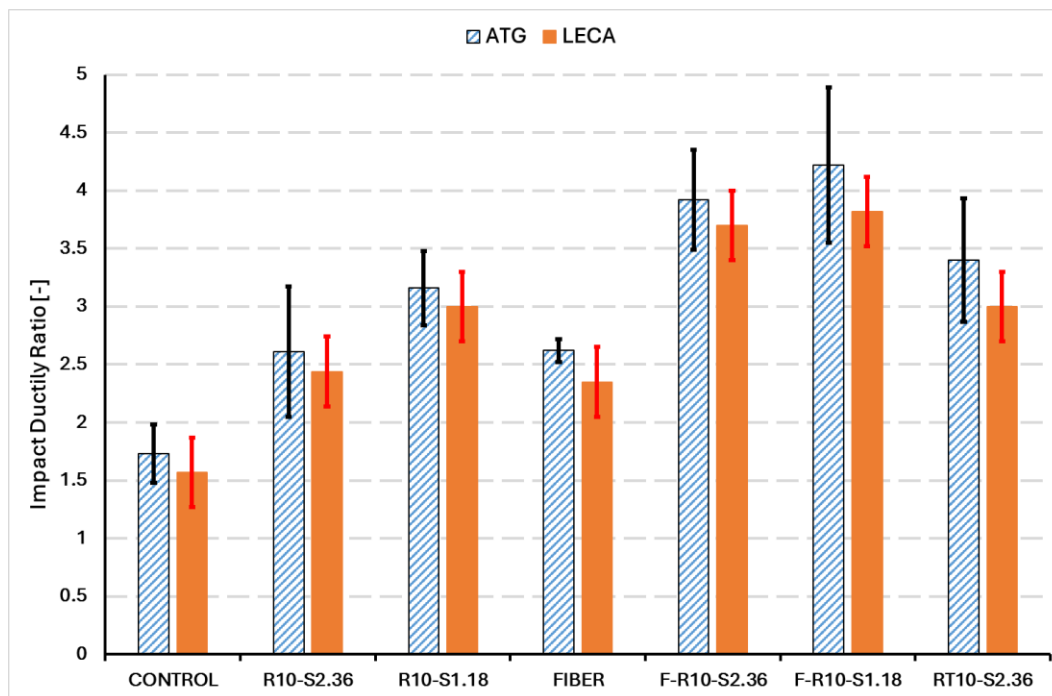


Figure 13: Impact Ductility Ratio of LWSCC with CMR and MSF Incorporation Using Different of LWCA Type

4. Conclusions

Based on the experimental results obtained in this study, the following conclusions were drawn:

- The ATG mixtures achieved 11% higher compressive strength and 21% higher modulus of elasticity than LECA, owing to their greater particle stiffness, angular shape, and stronger ITZ bonding.
- Increasing the CMR content from 10% to 30% reduced the compressive strength by up to 35%, whereas the IDR increased by 51-83%, confirming the strength-ductility trade-off in the rubberized LWSCC.
- A 10% CMR replacement balanced mechanical performance and impact resistance, with strength loss limited to 10-18% and full compliance with ACI 213R structural requirements.
- At equal replacement levels, S1.18 rubber particles produced better fresh and hardened performances than S2.36, with higher flowability, compressive strength, tensile strength, and IDR.

- The addition of 0.5% MSF increased the flexural and tensile strengths by up to 29% and 24%, respectively, and improved the IDR by over 45%, driven by crack-bridging and enhanced post-cracking load transfer.
- NaOH treatment recovered the compressive strength by 5.8% and 3.0% for the ATG and LECA mixtures, respectively, and improved the IDR, reflecting a stronger rubber-paste bond at the interfacial zone.
- All twenty-two mixtures met the EFNARC criteria for filling ability, passing ability, and segregation resistance, confirming that the addition of rubber and fiber did not impair the self-compacting behavior.
- ATG-based LWSCC with NaOH-treated rubber and MSF shows promising potential for structural applications, combining low self-weight, high impact resistance, local materials, and recycled tire rubber.
- For further investigations into its durability, long-term behavior, and large-scale structural validation are recommended to fully justify its practical field implementation

Author Contributions

M. S. planned the experiments, formal analyzed the data, and contributed to writing and editing. **A. H.** contributed to the experiments, supervised the experimental work, and reviewed the manuscript. **M. J.** supervised and contributed to review the manuscript and editing.

Statement of Conflicting Interests

The authors declare no financial or personal interests that may have impacted this study. The final version has been reviewed and approved by all writers. This paper has no funding, authorship, or publishing conflicts.

Data Availability

Data will be made available on request.

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